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MESOZOIC AND TERTIARY GRANITIC ROCKS IN IDAHO[1]

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ABSTRACT

There has been considerable speculation regarding the age of the granitic rocks which outcrop over a large part of Idaho. In the present paper pertinent data in published papers and the results of recent investigations by the writer are summarized. These show that most of the granitic rock belongs to a single mass known as the Idaho batholith and to outliers of it, but that there are also much younger granitic masses in the state. The Idaho batholith is shown to be post-Triassic and pre-Tertiary and probably to have been intruded near the end of the Jurassic. A mass of granite exposed over more than 200 square miles is shown to intrude the Idaho batholith and to be of Miocene or possibly Pliocene age.

FOREWORD

Since the earliest reconnaissance work in Idaho the great mass of granitic rock in the central part of the state has stood out as one of the most conspicuous features of its geology. During the past half-dozen years the writer has had occasion, in connection with areal and economic investigations made for the U.S. Geological Survey in cooperation with the Idaho Bureau of Mines and Geology,[2] to cross

[1] Published by permission of the Director, U.S. Geological Survey.

[2] C. P. Ross, "Copper Deposits Near Salmon, Idaho," *U.S. Geol. Survey Bull. 774* (1925); F. C. Schrader and C. P. Ross, "Antimony and Quicksilver Deposits in the Yellow Pine District, Idaho," *U.S. Geol. Survey Bull. 780-D* (1926); C. P. Ross, "A Disseminated Lead Deposit in Northern Boise County, Idaho," *Idaho Bureau of Mines and Geology, Pamphlet 20* (1926); "The Vienna District, Blaine County, Idaho," *Idaho Bureau of Mines and Geology, Pamphlet 21* (1927); "Ore Deposits in Tertiary Lava in

considerable parts of this mass and to study the granitic rocks in detail at several localities. At first, variation in character of the rocks was confusing, but with the advance of the work and a re-examination of doubtful areas the conviction has grown that the greater part of the granitic rocks belong essentially to one geologic unit fully worthy of the name "Idaho batholith" which is frequently applied to it. In addition, however, there are outlying masses, some of which are doubtless genetically related to the main batholith, but some of which are certainly much younger. It is the purpose of this paper to summarize the reasons for the writer's conclusion that the Idaho batholith is of early Cretaceous or possibly Jurassic age but that the younger granitic rock is of Tertiary, probably Miocene, age.

Owing to the incompleteness of the stratigraphic record in most parts of Idaho, some geologists have refrained from expressing any opinion as to the age of the granitic rocks, while others have been led into speculations with such divergent results as to becloud the situation. Here and there, however, evidence fixing the age within rather narrow limits is now available, and consideration of the known facts for the whole region, in the light of field acquaintance with a large part of it, leads to confidence that the conceptions of age expressed above are now well substantiated.

The accompanying sketch map is a generalized compilation of existing data regarding the distribution of granitic rocks in Idaho and adjoining regions. In its preparation all published geologic maps covering areas in Idaho have been utilized and data on maps by Westgate[1] and the writer,[2] now in course of publication by the U.S Geological Survey, have also been incorporated. Dashed-line boundaries are used only where no geologic maps are available. Outside

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the Salmon River Mountains, Idaho," *Idaho Bureau of Mines and Geology, Pamphlet 25* (1927); "Geology and Ore Deposits of Part of the Wallowa Mountains, Oregon," *U.S. Geol. Survey Bull.* (in preparation); "Geology and Ore Deposits of the Casto Quadrangle Idaho, *U.S. Geol. Survey Bull.* (in preparation); "The Thunder Mountain District, Idaho," *U.S. Geol. Survey Bull.* (in preparation); J. B. Umpleby, L. G. Westgate, and C. P. Ross, "Geology and Ore Deposits of the Wood River Region (Hailey Quadrangle), Idaho," *U.S. Geol. Survey Bull.* (in preparation.)

[1] J. B. Umpleby, L. G. Westgate, and C. P. Ross, *op. cit.*

[2] C. P. Ross, "Geology and Ore Deposits of the Casto Quadrangle, Idaho," *U.S. Geol. Survey Bull.* (in preparation).

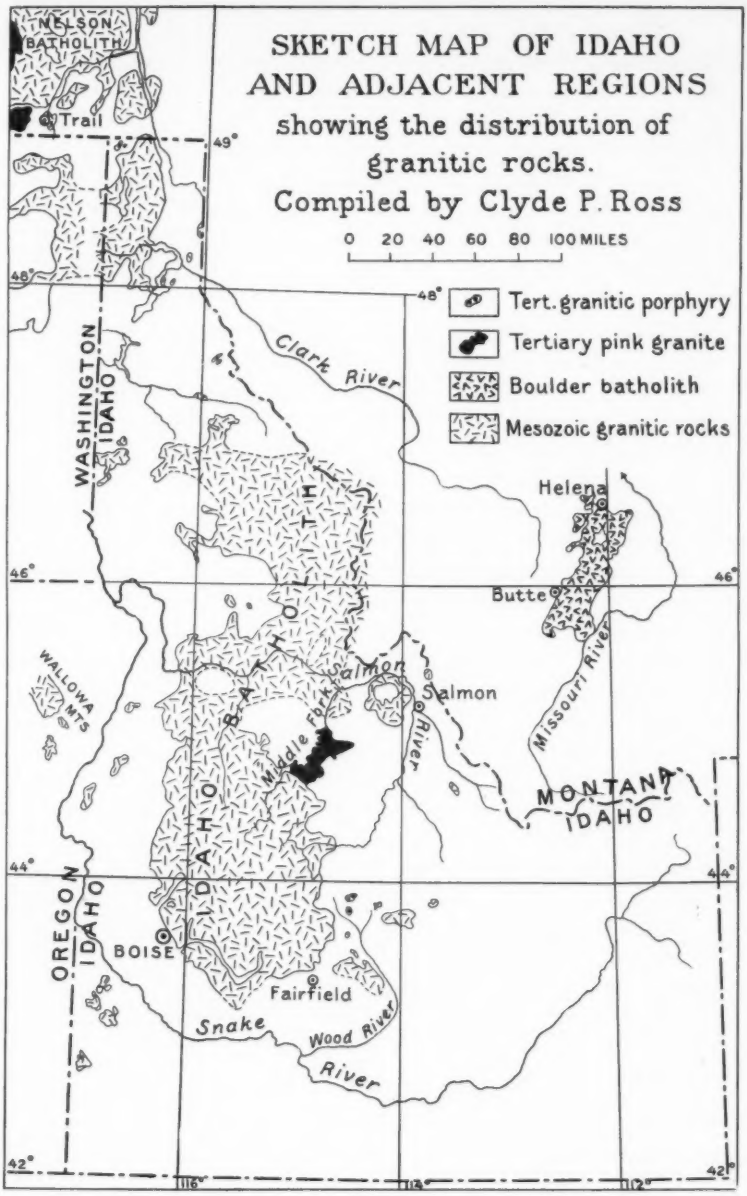
SKETCH MAP OF IDAHO
AND ADJACENT REGIONS
showing the distribution of
granitic rocks.
Compiled by Clyde P. Ross
0 20 40 60 80 100 MILES
Tert. granitic porphyry
Tertiary pink granite
Boulder batholith
Mesozoic granitic rocks
NELSON BATHOLITH
Trail
49°
48°
WASHINGTON
IDAHO
Clark River
Helena
46°
Butte
IDAHO BATHOLITH
WALLOWA MTS
Salmon
Salmon River
Middle Fork
Missouri River
MONTANA
IDAHO
44°
OREGON
IDAHO
BOISE
Fairfield
Snake
Wood River
River
42°
116°
114°
112°

FIG. 1

of the state only masses of importance in connection with the present discussion are shown. The more important published reports used are cited in the following descriptions.

GEOLOGIC RELATIONS OF THE IDAHO BATHOLITH

The Idaho batholith is composed mainly of quartz monzonite, although some facies, mainly marginal, are granodiorite, and minor amounts of other granitic rocks are included. It is now exposed over about 16,000 square miles extending from the vicinity of Boise northward through the center of Idaho into Montana. It is flanked on either side by numerous smaller bodies of granitic rock in Idaho and neighboring parts of Oregon and Montana. To the north there are masses of batholithic dimensions in the narrow northern end of Idaho and in nearby Washington and British Columbia.

Most of the western, all of the southern, and much of the eastern borders of the Idaho batholith are rimmed with Tertiary strata, mainly Miocene (?) volcanic rocks. In numerous places such rock rests on the eroded surface of the batholith, and it is clear that much of the part of the batholith now exposed was laid bare prior to the Tertiary volcanism and was covered by the flows. Although the volcanic rocks resting on the batholith are believed to be mainly of Miocene age, some may be as old as Oligocene.

Near its southeastern end the batholith[1] intrudes a thick series of Paleozoic strata. In this vicinity isolated granitic masses similar and probably satellitic to the batholith cut Paleozoic strata ranging in age up to Pennsylvanian.[2] Farther north on the east border of the batholith the bordering formations are mostly Algonkian quartzites and slates and Tertiary volcanic rocks, although Paleozoic rocks[3] may also exist; and the writer's recent work in this part of Idaho has shown the presence of an extensive area of Permian (?)[4]

[1] J. B. Umpleby, "Ore Deposits in the Sawtooth Quadrangle, Blaine and Custer Counties, Idaho," *U.S. Geol. Survey Bull. 580* (1915).

[2] J. B. Umpleby, "Geology and Ore Deposits of the Mackay Region, Idaho," *U.S. Geol. Survey, Prof. Paper 97* (1917). J. B. Umpleby, L. G. Westgate, and C. P. Ross, *op. cit.*

[3] J. B. Umpleby, "Some Ore Deposits in Northwestern Custer County, Idaho, *U.S. Geol. Survey Bull. 539* (1913).

[4] C. P. Ross, "Ore Deposits in Tertiary Lava in the Salmon River Mountains, Idaho," *Idaho Bureau of Mines and Geology, Pamphlet 25* (Aug. 1927), p. 7.

volcanic strata which are cut by the Idaho batholith. To the northeast the batholith extends into a part of Montana for which little geologic information is available but it is believed to be bordered there mainly by Belt (Algonkian) rocks. The northern part of the batholith, in Idaho, is intrusive into Belt rocks. On its west side the bordering formations, in addition to the extensive Tertiary volcanics of later origin, include pre-Tertiary sedimentary and volcanic strata which are intruded by it. The pre-Tertiary rocks along the part of the western boundary north of Salmon River are mostly so metamorphosed as to make correlation doubtful,[1] but along Snake River there are considerable thicknesses of Permian strata and less abundant Triassic beds, both of which include volcanic and sedimentary rocks.[2] Small granitic masses, presumably satellites, and also a projection from the Idaho batholith itself cut the Permian strata. The relations of the granitic rocks to the Triassic strata in this region are not definitely known although it is believed that the Triassic beds are intruded by them.[3] A short distance farther west in the Wallowa Mountains, Oregon, a granodiorite stock cuts Triassic beds and overlying rocks possibly as young as Jurassic.[4]

It appears from available data that the Idaho batholith and the majority of the neighboring stocks have steep sides, expanding downward. So far as present data go, there is no evidence that the Idaho batholith has a floor or is constricted at depth in the manner sug-

[1] F. A. Thomson, and S. M. Ballard, "Geology and Gold Resources of North-Central Idaho," *Idaho Bur. of Mines and Geology Bull. 7* (1924), pp. 20–24.

[2] These statements are based mainly on unpublished data, kindly supplied by F. B. Laney. See also D. C. Livingston and F. B. Laney, "The Copper Deposits of the Seven Devils and Adjacent Districts, Idaho," *Idaho Bur. of Mines and Geology Bull. 1* (1920), pp. 18–24. D. C. Livingston, "A Geologic Reconnaissance of the Mineral and Cuddy Mountain Mining Districts, Washington and Adams Counties, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet, 13*, pp. 4–6.

[3] Waldemar Lindgren, "A Geological Reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho," *U.S. Geol. Survey, Prof. Paper 27* (1904), p. 20.

[4] Waldemar Lindgren, "The Gold Belt of the Blue Mountains of Oregon," *U.S. Geol. Survey, 22d Ann. Rept.*, Part 2 (1901), pp. 586–87. C. P. Ross, "Geology and Ore Deposits of a Part of the Wallowa Mountains, Oregon," *U.S. Geol. Survey Bull.* (in preparation).

gested by Chamberlin;[1] but the depths of a few thousand feet to which canyons have been incised in the batholith may not be sufficient to test Chamberlin's hypothesis. Roof pendants, which are widely distributed over the exposed part of the batholith, indicate that the original surface of the batholith was but little above the tops of the present mountains of granitic rock.

GEOLOGIC RELATIONS OF OUTLIERS OF THE BATHOLITH IN IDAHO

Most writers have assumed that relatively small granitic masses in Idaho and neighboring parts of adjacent states are related in age and genesis to the Idaho batholith. In some places the preponderance of evidence favors such a view; in others the available data do not warrant a definite opinion; and in a few places there is definite evidence that the granitic rock is younger than the Idaho batholith. The available data on those of the first two groups are briefly summarized below. Data on granitic rocks believed to be younger than the Idaho batholith are given in subsequent sections.

Similarity in petrology and in relations to the surrounding rocks leads to the opinion that most of the granitic rock in the Wood River region,[2] in Lemhi County,[3] in western Idaho near Snake River,[4] and in the scattered exposures in the southwestern part of the state, is closely related to the main batholith. Most published reports[5] on the last-named region make no definite age assignment of the granitic rocks but show that the oldest Tertiary lava in the region rests on the eroded surface of granitic masses. In the southern

[1] R. T. Chamberlin, and T. A. Link, "The Theory of Laterally Spreading Batholiths," *Jour. Geol.*, Vol. XXXV, No. 4 (1927), pp. 319–54.

[2] J. B. Umpleby, L. G. Westgate, and C. P. Ross, *op. cit.*

[3] J. B. Umpleby, "The Geology and Ore Deposits of Lemhi County, Idaho," *U.S. Geol. Survey Bull. 528* (1913), pp. 42, 43.

[4] D. C. Livingston and F. B. Laney, "The Copper Deposits of the Seven Devils and Adjacent Districts," *Idaho Bur. of Mines and Geology Bull. 1* (1920), pp. 24–26.

[5] Waldemar Lindgren, "The Gold and Silver Veins of Silver City, De Lamar and Other Mining Districts in Idaho," *U.S. Geol. Survey, 20th Ann. Rept.*, Part 3 (1900), p. 117. A. M. Piper and F. B. Laney, "Geology and Metalliferous Resources of the Region about Silver City, Idaho," *Idaho Bur. of Mines and Geology Bull. 11* (1926), pp. 14–20. R. E. Sorenson, "The Geology and Ore Deposits of the South Mountain Mining District, Owyhee County, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet 22* (1927), p. 23.

part of the Seven Devils region some doubt is cast on the correlation by Livingston.[1] He notes that certain ore-bearing veins, probably related to granodiorite stocks, cut the Permian but not the Triassic strata, and reasons from this that the granodiorite in the area he studied may be older than the Triassic beds there exposed. This conclusion implies that the granodiorite is older than the Idaho batholith.

Farther north, in the Clearwater country, the granitic rock which appears here and there surrounded by the Columbia River basalt is probably to be correlated with the Idaho batholith in age and may represent a westward extension of the batholith itself beneath the lava.[2]

In northern Idaho some of the granitic rock, particularly the large mass which extends from Pend Oreille Lake northward into British Columbia, is regarded as probably related to the Idaho batholith.[3] This mass is reported by Kirkham and Ellis to be composed of granodiorite, quartz-monzonite, and granite. The southern part of it, described in detail by Gillson,[4] is a granodiorite closely similar to the more calcic facies of the Idaho batholith. Stewart[5] has pointed out that there are small masses of monzonite in the Coeur d'Alene district and elsewhere in northern Idaho petrographically different from the rock typical of the Idaho batholith, and he is inclined to regard these as late products of the same intrusive

[1] D. C. Livingston, "A Geologic Reconnaissance of the Mineral and Cuddy Mountain Mining Districts, Washington and Adams Counties, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet 13*, p. 19.

[2] Waldemar Lindgren, "A Geological Reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho," *U.S. Geol. Survey, Prof. Paper 27* (1904), p. 17. A. L. Anderson, "Mica Deposits of Latah County, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet 14*, p. 6. V. R. D. Kirkham, "Ground Water for Municipal Supply at Potlatch, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet 23* (1927), p. 4. V. R. D. Kirkham, "Underground Water Resources in the Vicinity of Orofino, Idaho, and of Lapwai, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet 24* (1927), p. 4.

[3] V. R. D. Kirkham and E. W. Ellis, "Geology and Ore Deposits of Boundary County, Idaho," *Idaho Bur. of Mines and Geology Bull. 10* (1926), pp. 35, 36.

[4] J. L. Gillson, "Granodiorites in the Pend Oreille District of Northern Idaho," *Jour. Geology*, Vol. XXXV, No. 1 (1927), pp. 1–31.

[5] C. A. Stewart, "A Comparison of the Coeur d'Alene Monzonite with Other Plutonic Rocks of Idaho," *Jour. Geology*, Vol. XXII (1914), pp. 684–88.

activity. Since the rocks they cut are all old, however, definite evidence as to age relations is not available.

GRANITIC ROCKS IN NEIGHBORING REGIONS RELATED TO THE IDAHO BATHOLITH

There are numerous exposures of granitic rocks in eastern Oregon and Washington, southeastern British Columbia, and western Montana. Many of these, so far as the incomplete available information goes, are broadly similar in petrology and geologic relations to the outliers of the batholith in Idaho. Some of those in Montana and British Columbia, however, are so related to late Mesozoic and Tertiary rocks as to suggest a later age.

In eastern Oregon Lindgren[1] has mapped fourteen masses of granitic rock. He shows that some of these cut Triassic strata, and notes that beds of Chico (Upper Cretaceous) age along the lower John Day River are undisturbed by the structural disturbances associated with the intrusion. He concludes therefore that the intrusion is post-Triassic and pre-Chico in age. This conclusion is strengthened by more recent and detailed work in the Wallowa Mountains,[2] in the northeastern part of the region he covered. The strata in these mountains from which Lindgren[3] collected Triassic fossils are now known to be of Lower Triassic age and to be overlain by a thick unfossiliferous series of sedimentary and volcanic strata which probably represent deposition later in the Triassic and possibly even in Jurassic time. The deformation of these rocks is clearly related to the intrusion of a granodiorite stock, and is intense, even more so than most of the similar deformation in Idaho. The granodiorite has considerable resemblance to some of the more calcic phases of the Idaho batholith.

In eastern Washington there are also extensive exposures of granitic rocks. The published descriptions indicate that they vary considerably in petrologic character.[4] Some facies are similar to the

[1] Waldemar Lindgren, "The Gold Belt of the Blue Mountains of Oregon," *U.S. Geol. Survey, 22d Ann. Rept.*, Part 2, Pl. LXIV (1901), pp. 585–88, 596.

[2] C. P. Ross, "Geology and Ore Deposits of a Part of the Wallowa Mountains, Oregon," *U.S. Geol. Survey Bull.* (in preparation).

[3] Lindgren, *op. cit.*, pp. 580, 581.

[4] J. B. Umpleby, "Geology and Ore Deposits of Republic Mining District," *Washington Geol. Survey Bull. 1* (1910), pp. 17, 18. C. E. Weaver, "Geology and Ore

rock characteristic of the Idaho batholith while others differ materially. The larger granitic masses in this region cut strata of Carboniferous and possibly of early Mesozoic age, and were extensively eroded before the Tertiary (Miocene?) volcanic and sedimentary strata were laid down on them.

In southeastern British Columbia there are a number of granitic masses,[1] and most of those which have any resemblance to the Idaho batholith belong to the Nelson batholith or its outliers. This batholith has been correlated with the granitic rocks of northern Idaho,[2] although the two masses are not actually connected at the surface. The Nelson batholith and related granitic masses have been mapped in a number of districts[3] in British Columbia, and intrude Carboniferous strata, whereas pebbles from them are included in Upper Cretaceous (Upper Blairmore) conglomerate.[4] The intrusion of the Nelson batholith is generally regarded by the Canadian geologists as related to orogenic movements which they regard as of Jurassic age. The rock of the Nelson batholith and its outliers ranges in composition from granite to granodiorite. There is more variation both in composition and appearance than is characteristic of the Idaho

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Deposits of the Covada Mining District," *Washington Geol. Survey Bull 16* (1913), pp. 23–27, 30, 31. Howland Bancroft, "The Ore Deposits of Northeastern Washington," *U.S. Geol. Survey Bull. 550* (1914), pp. 16–18. J. T. Pardee, "Geology and Mineral Deposits of the Colville Indian Reservation, Washington," *U.S. Geol. Survey Bull. 677*, pp. 30–34. O. P. Jenkins, "Lead Deposits of Pend Oreille and Stevens Counties, Washington," *Washington Dept. of Cons. and Dev. Bull. 31* (Geol. Series) (1924), pp. 27–30.

[1] R. A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Canadian Geol. Survey Mem. 38* (1912), pp. 281–318.

[2] V. R. D. Kirkham and E. W. Ellis, "Geology and Ore Deposits of Boundary County, Idaho," *Idaho Bureau of Mines and Geology Bull. 10* (1926), p. 35.

[3] R. G. McConnell and R. W. Brock, "West Kootenay Sheet, B.C.," Map sheet No. 792, accompanying *Geol. Survey of Canada, Ann. Rept. for 1901.* New series, Vol. XIV. C. W. Drysdale, "Geology of Franklin Mining Camp, British Columbia, *Geol. Survey of Canada Mem. 56* (1915), pp. 48, 55–62. S. J. Schofield, "Geology of Cranbrook Map Area, B. C.," *Geol. Survey of Canada Mem. 76* (1915), pp. 78–85. M. F. Bancroft, "Investigations in the Slocan District, B.C.," *Geol. Survey of Canada, Summary Rept.* (1917), Part B (1918), p. 35. S. J. Schofield, "Geology and Ore Deposits of Ainsworth Mining Camp, B.C.," *Geol. Survey of Canada Mem. 117* (1920), pp. 22–23.

[4] S. J. Schofield, "Geology and Ore Deposits of Ainsworth Mining Camp, B.C.," *Geol. Survey of Canada Mem. 117* (1920), pp. 22–23.

batholith, but some facies of the rock of the two batholiths have much in common.

In western Montana some of the numerous granitic masses are doubtless related to the Idaho batholith, whose northeastern extension occupies a large area there. The masses mapped by Calkins[1] in northwestern Montana are similar to those in northern Idaho although he makes no age assignments. Those along the western boundary of Beaverhead County are similar to and in part continuous with rocks in Lemhi County, Idaho, which are tentatively considered to be related to the Idaho batholith. Much of the granitic rock in western Montana, however, is generally considered to belong to the Boulder batholith or its outliers, and, as will be shown elsewhere, there is reason to believe that the Boulder batholith is younger than the Idaho batholith.

YOUNG GRANITIC ROCKS IN IDAHO

Granitic rocks clearly younger than the Idaho batholith are known along the Middle Fork of Salmon River and in and near the Wood River region in south-central Idaho[2] and probably exist elsewhere in the state, although certainly in masses that are small in comparison to the Idaho batholith. The largest known mass of such rock in Idaho is that recently mapped along the Middle Fork of Salmon River. This will be described in detail in a report[3] now in preparation for publication by the United States Geological Survey. The following account is abstracted from this report. The main body of the work, consisting dominantly of pink granite, has been mapped over a little more than 200 square miles and extends northward an unknown distance beyond the area studied. This work ranges in composition from granite, in part granophyric, to quartz monzonite, and its essential minerals are quartz, microcline, oligoclase, biotite,

[1] F. C. Calkins, "A Geological Reconnaissance in Northern Idaho and Northwestern Montana," *U.S. Geol. Survey Bull. 384*, Pl. 1 (1909), pp. 43–47.

[2] C. P. Ross: "Ore Deposits in Tertiary Lava in the Salmon River Mountains, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet 25* (1927), p. 10. "Salient Features of the Geology of Southcentral Idaho," *Jour. Washington Acad. of Sci.*, Vol. XVIII, No. 9 (1928), pp. 267, 268.

[3] C. P. Ross, "Geology and Ore Deposits of the Casto Quadrangle, Idaho," *U.S. Geol. Survey Bull.* (in preparation).

and in places hornblende. Close by the main mass there are also a number of small, closely related masses varying in area from a fraction of a square mile up to about 4 square miles. One of these is similar in composition to the main body but most are characterized by more abundant hornblende. The hornblendic rocks have, in different exposures, the composition of granite, quartz monzonite, and quartz diorite. Their essential minerals are andesine or slightly more sodic plagioclase, hornblende, biotite, and quartz. In addition there are numerous small dikes and irregular masses of fine-grained, porphyritic rocks clearly related to the pink granite. These include granophyre, granite porphyry, dacite porphyry, andesite porphyry, quartz-hornblende, monzonite porphyry, and lamprophyre.

The main mass of the pink granite is exposed along the axis of a broad anticline which involves both Permian (?) and Miocene (?) volcanic strata and is broken by numerous faults. The bottom of the granite is exposed in two areas, and structural relations indicate that it was intruded as a laccolithic mass along or near the base of the Permian (?) volcanics, although in places it transgresses them completely and penetrates the overlying Tertiary strata. Underneath the pink granite, and also in places on its upper contact, there is a complex composed of intensely altered sedimentary strata, mainly Algonkian, and of granitic rocks probably related to the Idaho batholith. The sedimentary strata are injected to different degrees by igneous material believed to have been derived in part from the granitic rock of Idaho batholith age, in part from the Miocene (?) pink granite, and some of them are typical injection gneisses. The presence of pink granite stringers in the injection gneiss is especially noteworthy in view of the fact that the cover over the laccolithic mass was little if any more than a mile thick; but since the gneissic structure of the injected rocks had already been developed by the Idaho batholith, it favored further injection by the pink granite.

The pink granite mass appears to have a form resembling that postulated by Chamberlin and Link[1] although no evidence was observed of overthrust faulting related to the intrusion such as is suggested by Link's experiments.

The only other rocks of approximately granitic texture in Idaho

[1] R. T. Chamberlin and T. A. Link, *op. cit.*

which have been proved to be of Tertiary age are those in the northwestern part of the Wood River region, Blaine County. Westgate[1] mapped in this locality a complex of irregular stocks and large dikes ranging in composition from granite porphyry to diorite porphyry and numerous related dykes which are smaller, finer grained, and most of which have the composition of rhyolite and andesite. He states that a number of the dikes cut the Miocene (?) lava. Similar more or less porphyritic granitic rocks were noted by C. H. Behre in the Sawtooth quadrangle a short distance farther west. His opinion, expressed orally to the writer, is that these also are of Tertiary age, although since his studies are uncompleted he cannot make a positive statement. Likewise Piper, in connection with his study of groundwater conditions on Camas Prairie,[2] noted similar rocks in the mountains about 10 miles northeast of Fairfield, although he did not describe them or map them separately in his published report. He states that these granitic porphyries are close to and apparently related to rhyolitic lava of probable late Miocene age. Investigations by the Idaho Bureau of Mines and Geology, as yet unpublished, indicate that intrusive masses of similar age exist elsewhere in the state.

YOUNG GRANITIC ROCKS IN NEIGHBORING REGIONS

The granitic rocks in Montana not closely related to the Idaho batholith belong, at least in large part, to the Boulder batholith or its satellites. Data on the geologic relations of these in the districts where they have been most studied are briefly presented below in the order in which the work was published.

In the Marysville district, according to Barrell,[3] the oldest intrusives are of latest Cretaceous or more probably early Eocene age. The Marysville batholith, composed of quartz diorite, is younger than these but since it intrudes Belt strata there is no way to fix its age directly. Weed[4] shows that the Boulder batholith itself, which

[1] J. B. Umpleby, L. G. Westgate, and C. P. Ross, *op. cit.*

[2] A. M. Piper, "Groundwater for Irrigation on Camas Prairie, Camas and Elmore Counties, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet 15* (1926).

[3] Joseph Barrell, "Geology of the Marysville Mining District, Montana," *U.S. Geol. Survey, Prof. Paper 57*, Pl. 1 (1907), pp. 44–63.

[4] W. H. Weed, "Geology and Ore Deposits of the Butte District, Montana," *U.S. Geol. Survey, Prof. Paper 74* (1912), p. 29.

consists mainly of hornblendic quartz, monzonite, and diorite, intrudes rocks of definitely Cretaceous age, and that nearby strata of "Laramie" (Cretaceous) age are involved in the folding associated with the intrusion. It also intrudes andesite which Weed considers to be of Eocene age, and he therefore concludes tentatively that the batholith is Miocene. Knopf,[1] however, on the basis of some poorly preserved fossils, holds that the andesite is of late Cretaceous age, and states that unconsolidated lignite-bearing sediments of possible Oligocene age rest on the granitic rock in places. He therefore concludes that available evidence points to a late Cretaceous age for the Boulder batholith.

In the vicinity of Philipsburg Calkins[2] describes a number of stocks and other intrusive masses, varying in composition from granite to diorite. Some of these cut strata of Colorado (Upper Cretaceous) age and are overlain unconformably by strata of not later than Miocene age. This fixes the age of the granitic rocks in the Philipsburg district more closely than is possible for any of the larger intrusive bodies in the region here considered, It is unfortunate that the relations between them and the larger batholith cannot be definitely determined.

In the part of British Columbia formerly known as West Kootenay, which adjoins the northwest corner of Idaho, Brock[3] has described a number of intrusive rocks of Tertiary age, and shows them to be distinctly later than the Nelson batholith which occupies most of this region. The largest of these Tertiary intrusives are the Valhalla granite of post-Cretaceous age and the Rossland alkali granite and syenite. The latter intrudes the Valhalla granite and also cuts some of the lava of Tertiary, probably Miocene, age. The Rossland

[1] Adolph Knopf, "Ore Deposits of the Helena Mining Region, Montana," *U.S. Geol. Survey Bull. 527* (1913), pp. 28–36.

[2] F. C. Calkins, "The Philipsburg Folio," *U.S. Geol. Survey, Geol. Atlas of the U.S.*, Folio 196 (1915), pp. 11–17, 23.

[3] R. G. McConnell and R. W. Brock, "West Kootenay Sheet, B.C.," Map Sheet 792, accompanying *Geol. Survey Canada, Ann. Rept. for 1901*, new series, Vol. XIV. R. W. Brock, "Kootenay District," *Geol. Survey of Canada, Ann. Rept.*, new series, Vol. XIII (1900) (1903), pp. 62–84. "Preliminary Report on the Boundary District, B.C.," *Geol. Survey of Canada, Ann. Rept.*, new series, Vol. XV (1902–1903) (1906), pp. 104–5. "Preliminary Report on the Rossland, B.C., Mining District," *Geol. Survey of Canada*, Separate Publication No. 939 (1906), pp. 14–16.

granite appears to be closely similar to the Miocene (?) pink granite on the Middle Fork of Salmon River, central Idaho. Like the latter it is pink, cuts Tertiary lava, has numerous associated granophyric and other dikes, and has ore deposits associated with it. Some facies of the Rossland granite are more alkalic than any known in Idaho. The Rossland granite is shown in part in the northwest corner of the accompanying map but the Valhalla granite is west and north of the area represented.

In and near Franklin Mining Camp, southern British Columbia,[1] there are several intrusive bodies known to be of Tertiary age and younger than the main batholithic mass in this region. These comprise monzonite stocks intrusive into sedimentary rocks of supposed Eocene or Oligocene age and some smaller intrusions of porphyritic syenite, augite syenite, pyroxenite, and shonkinite, which are even younger than the monzonite.

In eastern Washington there are dikes of monzonite porphyry which Bancroft[2] regards as of late Mesozoic or perhaps early Tertiary age.

AGE OF THE IDAHO BATHOLITH

In the earlier accounts[3] the Idaho batholith was considered Archean, because such masses of crystalline rock were generally so considered. Lindgren[4] in 1898 cast doubt on this assignment. He recognized the intrusive, igneous character of the granite and suggested that the mineral veins in it were of Cretaceous or early Tertiary age. In a later report[5] he considers the batholith to be probably post-Triassic in age. Umpleby,[6] mainly because of his interpretation

[1] C. W. Drysdale, "Geology of Franklin Mining Camp, British Columbia," *Geol. Survey of Canada Mem. 56* (1915), pp. 74–84. 103.

[2] Howland Bancroft, *op. cit.*, pp. 16, 17.

[3] G. H. Eldridge, "A Geological Reconnaissance across Idaho," *U.S. Geol. Survey, 16th Ann. Rept.*, Part 2 (1895), pp. 224–25.

[4] W. Lindgren, "Mining Districts of the Idaho Basin and Boise Ridge, Idaho," *U.S. Geol. Survey, 18th Ann. Rept.*, Part 3 (1898), pp. 630–31.

[5] W. Lindgren, "A Geological Reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho," *U.S. Geol. Survey, Prof. Paper 27* (1904), p. 20.

[6] J. B. Umpleby, "Geology and Ore Deposits of Lemhi County, Idaho," *U.S. Geol. Survey Bull. 528* (1913), p. 43.

of the physiographic history of the region, considers that the batholith is of Cretaceous or early Eocene age. Most later writers follow Umpleby. Kirkham,[1] however, in his more recent papers has considered the granitic rocks in Idaho to be "Jurassic, Cretaceous or Eocene," presumably because of his correlations of the granitic rock in northern Idaho[2] with the Nelson batholith of British Columbia, which is Jurassic.

The relations between the Idaho batholith and surrounding rocks, as shown in this paper, prove that the batholith is later than Permian and probably Triassic strata, and much older than the Miocene (?) volcanic rocks that rest on its eroded surface. Most of the surrounding masses apparently related to it cannot with available evidence be dated more closely than the main batholith but in eastern Oregon and southeastern British Columbia the age of certain masses can be more definitely determined. The granitic rock in eastern Oregon, at least in the Wallowa Mountains, is younger than strata of Triassic and possibly of Jurassic age and is older than the Chico (Upper Cretaceous). The Nelson batholith in British Columbia is younger than Carboniferous strata and older than Upper Blairmore (Upper Cretaceous) time, and is related to orogenic disturbances which apparently took place in the Jurassic. The ages of the two granitic masses are, therefore, Jurassic to Lower Cretaceous. Contemporaneity between the Idaho batholith and these two masses cannot be proved by direct evidence, but accords with the known facts.

The principal uncertainty as to the age of the Idaho batholith is in the matter of the length of time which elapsed between its intrusion and the deposition of the Miocene (?) volcanic rocks on its eroded surface. On the basis of estimates of length of erosion given below it is thought that this interval may have been sufficiently long to correspond to the Oligocene, Eocene, and part of the Cretaceous, and that the batholith therefore may be at least as old as Cretaceous.

[1] V. R. D. Kirkham, "Groundwater for Municipal Supply at Potlatch, Idaho," *Idaho Bur. of Mines and Geology, Pamphlet 23* (June, 1927), p. 4. "Underground Water Resources in the Vicinity of Orofino, Idaho and of Lapwai, Idaho;" Idaho Bureau of Mines and Geology, *Pamphlet 24* (July, 1927), p. 4.

[2] V. R. D. Kirkham and E. W. Ellis, "Geology and Ore Deposits of Boundary County, Idaho," *Idaho Bur. of Mines and Geology Bull. 10* (1926), pp. 35, 36.

The thickness of the original cover over the Idaho batholith must have been great. This cover consisted of strata of the Belt series with an aggregate thickness of some tens of thousands of feet. Neither the horizon to which the top of the batholith penetrated nor the structure of the Belt rocks involved are known, but an estimate of a minimum depth of cover of one mile is probably conservative. This great mass of rock, largely quartzitic, was swept away over thousands of square miles and the upper part of the batholith itself attacked by erosion before the Tertiary strata were laid down. As already noted, the distribution of roof pendants is such as to show that, except in the canyons incised in it, the amount of granitic rock eroded has been small. On this basis, determination of the time required to erode a broad region to a depth of a mile would give a measure of the minimum time which elapsed between the intrusion of the batholith and Tertiary volcanism.

Ferguson[1] has recently made estimates by four widely different methods of the amount of erosion which has taken place in the Alleghany district, California, since the gold lodes there were formed. The agreement in the results arrived at by the four methods is sufficiently close, in spite of the numerous assumptions necessary, to make it appear highly probable that the results may be regarded as fair approximations. One of these methods makes use of estimates of the rate of erosion based on Dole and Stabler's[2] data. Their estimates do not include allowance for the amount of material transported by rolling on stream bottoms, but Ferguson makes estimates of this amount according to methods used by Gilbert[3] and by Humphreys and Abbott.[4] He concludes that at the present time the Alleghany district is being worn down at a rate of about 125 feet per million years. Physiographic considerations lead him to believe that the present rate is somewhat faster than the average since the formation of the

[1] H. G. Ferguson, "Lode Deposits of the Alleghany District, California," *U.S. Geol. Survey, Prof. Paper.* (in preparation).

[2] R. B. Dole and Herman Stabler, "Denudation," *U.S. Geol. Survey, Water Supply Paper 234* (1919), pp. 78–93.

[3] G. K. Gilbert, "Transportation of Débris by Running Water," *U.S. Geol. Survey, Prof. Paper 86* (1914), p. 230.

[4] A. G. Humphreys and H. L. Abbott, *Physics and Hydraulics of the Mississippi* (1867), p. 147.

gold lodes of that district. He considers that this average was 90–100 feet per million years and shows that such a rate is in accord with the probable amount of erosion in Eocene time in this district. The physiographic history of the Sierra Nevada during Mesozoic and early Tertiary time is sufficiently similar to that of central Idaho for the rates of erosion in the two regions to be comparable. If it is assumed that the rate of lowering of the surface over the Idaho batholith was 100 feet per million years during the period under discussion the time interval would be 52,800,000 years. If Ferguson's lower figure is taken, the time interval would be about 58,700,000 years.

TABLE I

ESTIMATES OF THE LENGTH OF THE TERTIARY AND CRETACEOUS (IN MILLIONS OF YEARS)

PERIOD	BARRELL		PERIOD	HOLMES	
	Minimum	Maximum		By Adding Successive Cycles	From Radioactive Minerals
Pliocene	6	7.5	Upper Tertiary	30	35
Miocene	12	14			
Oligocene	16	16			
Eocene	20	26	Lower Tertiary	30	25
Upper Cretaceous	40	50	Upper Cretaceous	30	.....
Lower Cretaceous (Comanche)	25	35	Lower Cretaceous	30	.....

The best recent estimates of the length of geologic time are those of Barrell[1] and of Holmes.[2] Their figures for the period here considered are shown in Table I.

Barrell's figures are more detailed and, for the period here considered, somewhat larger than those of Holmes. The smaller estimate given above of the time needed to remove the cover from the Idaho batholith exceeds Barrell's maximum estimate of the combined length of Oligocene and Eocene time by 10,800,000 years and his minimum by 16,800,000 years. If erosion was at the rate of 125 feet per million years (Ferguson's estimate for the present rate of denuda-

[1] Joseph Barrell, "Rhythms and the Measurement of Geologic Time," *Bull. Geol. Soc. America*, Vol. XXV (1917), pp. 884–85.

[2] Arthur Holmes, *The Age of the Earth*, p. 78. New York: Harper Bros., 1927.

tion of Alleghany, California) the time required would still exceed Barrell's minimum estimate of Oligocene and Eocene time by over 2,000,000 years. The average rate over this period in central Idaho was obviously less than the present rate in the Sierra Nevada and the thickness of the cover over the batholith was probably more rather than less than that assumed. Hence it appears that the time interval between batholithic intrusion and Tertiary volcanism was more than sufficient to account for all of pre-Miocene Tertiary time and that the Idaho batholith must be at least as old as Cretaceous.

The assignments of the batholithic activity to late Cretaceous or early Eocene in recent publications are all based on Umpleby's[1] analysis of the evidence. His work is the only attempt to evaluate the evidence as a whole since Lindgren[2] showed that the granitic rocks were intrusive into the surrounding strata and are not the basement on which the latter rest. Umpleby reasoned that the Idaho batholith accompanied the uplift which initiated erosion, culminating in an erosion surface which he considered to be of Eocene age, and therefore that the batholith was of late Cretaceous or early Eocene age. In support of his view he presented evidence to show that the granitic rocks were more closely related in distribution to Eocene, than to Mesozoic sedimentary strata; but in an earlier paper[3] he considered that granitic rock in eastern Washington was intruded "in the Mesozoic and possibly about the middle of that era," because the granitic mass was truncated by a peneplain of supposed Eocene age and had Tertiary strata lapping up on its sides. On physiographic evidence he assigned the oldest of the Tertiary formations here to the Oligocene, because it lay mainly near the bottom of a valley which, according to his interpretation, had been carved in the pene-

[1] J. B. Umpleby, "An Old Erosion Surface in Idaho; Its Age and Value as a Datum Plane," *Jour. Geol.*, Vol. XX (1912), pp. 139–47. "Geology and Ore Deposits of Lemhi County, Idaho," *U.S. Geol. Survey Bull. 528* (1913), pp. 42–43.

[2] Waldemar Lindgren, "Mining Districts of the Idaho Basin and Boise Ridge, Idaho, *U.S. Geol. Survey, 18th Ann. Rept.*, Part 3 (1898), pp. 630–31. "The Gold and Silver Veins of Silver City, De Lamar and Other Mining Districts in Idaho," *U.S. Geol. Survey, 20th Ann. Rept.*, Part 3 (1900), pp. 79, 195–96. "A Geological Reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho," *U.S. Geol. Survey, Prof. Paper 27* (1904), pp. 17–20.

[3] J. B. Umpleby, "Geology and Ore Deposits of Republic Mining District," *Washington Geol. Survey Bull. 1* (1910), p. 18.

plain in Oligocene time. In this connection it may be noted that since then Uglow[1] has described an apparently similar valley in southern British Columbia in which strata containing fossil plants of Eocene age have been deposited. With this exception, and the consequent earlier dating of events, Uglow's interpretation of the physiography is similar to Umpleby's, and as Umpleby's papers refer to the peneplain remnants near Republic, Washington, as part of the same surface that he has described in Idaho, his opinion that the Idaho batholith may be as young as Eocene is founded on inadequate data.

All the granitic rocks of apparent Tertiary or late Cretaceous age in Idaho and neighboring regions are known to be later than either the Idaho batholith or the probably related Nelson batholith, with the exception of those in Montana. Knopf[2] has suggested that the Boulder batholith in southwestern Montana may be genetically related to the Idaho batholith, but on the basis of petrology, general geologic relations, and proximity, the Idaho batholith has a much closer affinity to the granodiorite of the Wallowa Mountains, Oregon, and the Nelson batholith of British Columbia, than to the Boulder batholith. Both Weed's conclusions based on his work near Butte and Barrell's data obtained at Marysville indicate that the Boulder batholith is of Tertiary age, distinctly younger than the Idaho batholith as interpreted in this paper. Thus the available evidence favors the conception that the Boulder batholith is somewhat younger than the Idaho batholith although distinctly older than the Miocene (?) pink granite. This is in approximate accord with Lindgren's[3] suggestion of an eastward migration of intrusive igneous activity.

It may be merely a coincidence that the assignment of the Idaho batholith to a possible Jurassic age accords more closely with Harker's[4] conception of the igneous cycle than the theory of a later age now current. Harker postulates that the usual succession is (1) ex-

[1] W. L. Uglow, "Cretaceous Age and Early Eocene Uplift of a Peneplain in Southern British Columbia," *Bull. Geol. Soc. America*, Vol. XXXIV (1923), pp. 561–72.

[2] Adolph Knopf, *op. cit.*

[3] Waldemar Lindgren, "Igneous Geology of the Cordilleras and Its Problems," *Problems of American Geology* (1915), pp. 261–63.

[4] Alfred Harker, *The Natural History of Igneous Rocks* (1909), pp. 23–29.

trusion, (2) batholithic intrusion, and (3) dike intrusion. The first of these would be represented by the extensive lava flows of Permian and Triassic age, the second by the Jurassic (?) Idaho batholith, and the third by the aplitic and other related dikes which cut it. The cycle would then be duplicated in Tertiary time since the succession of lava flows, large-scale granitic intrusion, and finally intrusion of numerous dikes in the vicinity of the present Middle Fork of Salmon River is in exact accord with Harker's succession.

To summarize, the Idaho batholith is probably younger than Triassic, and probably as old as Lower Cretaceous, at least as old as Cretaceous. As batholiths of such magnitude are generally related to major orogenic disturbances, it is reasonable to regard this batholith as one of the products of widespread diastrophism which occurred in the Cordilleran region near the end of the Jurassic period.

AGE OF THE YOUNG PINK GRANITE

The pink granite along the Middle Fork of Salmon River is the only known large mass of granitic rock in Idaho materially younger than the Idaho batholith. This rock not only cuts the Idaho batholith, but in a few places extends up to and intrudes the lower strata of the Tertiary volcanics, which lie unconformably on the Idaho batholith. Since the pink granite is an irregular laccolithic mass intruded near the base of the Permian (?) volcanics, it is in contact with the Tertiary strata in relatively few places, but in each of these the contact clearly indicates or strongly suggests intrusive relations. In the Casto quadrangle, on the ridge east of the Middle Fork between Warm Spring and Aparejo creeks the intrusive character of the irregular contact is evidenced by the presence of chilled facies of the granite and by baking, silicification, and fracturing of the lava in places immediately above the contact. Farther up the Middle Fork a block of red flow-banded lava similar to some of the flows in the Tertiary volcanics above is included in the pink granite. This block is roughly 30 by 45 feet in plan, has an exposed height of 20 feet, and is 1,000 feet vertically below the base of the Tertiary volcanics in this vicinity. In several places some of the numerous granophyre dikes related to the pink granite intrude the lower few hundred feet of the Tertiary volcanics.

The pink granite lies along the axis of a broad anticline which involves all the Tertiary strata of the region in such a way as to indicate that its intrusion and the folding are genetically related. Furthermore in several places the pink granite and related dikes are exposed along northeast-trending faults which break this anticline, and although actual intrusive contacts along these faults were not observed, the distribution of the granitic rocks and the fact that the granite shows no evidence of the fracturing associated with the faulting leave little doubt as to the relationship.

The pink granite, in short, is definitely younger than the lower part of the Tertiary volcanic strata and is associated with orogenic movements which took place subsequent to the formation of all the Tertiary strata in this vicinity. The exact age of these Tertiary rocks has not been determined, but it is believed on the basis of the relations to plant-bearing beds farther east that the upper part of the series near the Middle Fork is not older than middle Miocene. On this basis, the pink granite is at least of late Miocene and possibly of Pliocene age.

CERTAIN TOPOGRAPHIC FEATURES OF NORTH-EASTERN OREGON AND THEIR RELATION TO FAULTING

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ABSTRACT

The mountains which form the granite batholith of north-central Idaho are of pre-Miocene age, while the Blue Mountains and Wallowa Range of Oregon and the Seven Devils and Cuddy Mountain system of western Idaho are post-Miocene. The latter have been formed by uplift along two post-Miocene faults, which intersect at right angles in the vicinity of Snake River, and the development of the drainage pattern of the region, including the canyon of Snake River, has been controlled almost entirely by these faults.

GEOGRAPHICAL POSITION AND TOPOGRAPHIC FEATURES

The region to be discussed lies directly west of the great mountain uplift of Idaho, which is largely a granitic batholith and a part of the Rocky Mountain system, and east of the lava-covered Columbia Plateau. This plateau extends, within the states of Oregon, Washington, and portions of Idaho, from the Rocky Mountain uplift to the Cascade Range. The region to be described is a portion of the borderland between these two great geologic and topographic provinces and partakes somewhat of the character of each. It embraces part of a country lying between latitudes 44° 15′ and 45° 00′, and between longitudes 116° 45′ and 118° 30′. From south to north it extends from the neighborhood of Burnt River, Oregon, to the mouth of the Grande Ronde River in Washington, and from west to east it extends from the Blue Mountains of Oregon to the Seven Devils Range of Idaho. The study is confined chiefly to that territory lying south of the Wallowa Range of Oregon.

In general the region might be considered as a rough and broken basaltic plateau, with an average elevation of 3,500–4,000 feet. This plateau has been deeply intrenched by many of the streams, and portions of it have been uplifted to higher elevations by the uprising of certain blocks along fault scarps and fracture lines.

GEOGRAPHICAL POSITION AND TOPOGRAPHIC FEATURES

The mountains, which protrude through the plateau, rise to elevations of 8,000–10,000 feet. The most prominent of these are the Blue Mountains. These may be considered as beginning in the low domelike uplift of Craig Mountain in northern Idaho (see Fig. 1). The range then swings southward just to the east of Walla Walla and Pendleton, separating the Columbia Plateau from the alluvial valleys of the Grande Ronde and Powder rivers in Oregon. The range then spreads out to the south, forming a broad complex mountain group whose northern boundary swings eastward in a concave arc to the Idaho line at Snake River. From this point spurs extend northeast across Snake River into Idaho, and connect the Blue Mountain system with the range which is partly buried beneath basaltic flows and which trends northeast parallel to Snake River canyon.

This northeastward-trending range on the east side of Snake River, which is bounded on the east by the Weiser Valley, is composed of several partly isolated mountains, separated from one another by portions of the basalt plateau. From north to south these mountains are known as the Seven Devils, Cuddy Mountain, Hitt Mountain, and Iron Mountain, respectively.

Within the curve of the Blue Mountain arc rises the Wallowa Range of Oregon, isolated from the neighboring ranges (see Fig. 1). It is separated from the Seven Devils Range by the canyon of Snake River, and from the Blue Mountain system by a broken plateau country and the alluvial valleys of the Powder and Grande Ronde rivers. The southern border of the Wallowa Range trends northwest. Its eastern border apparently trends northeast, but is not well defined from the basaltic plateau into which it merges. The western border consists of abrupt fault scarps which separate the range from the Grande Ronde Valley. To the north it is bounded by the high basaltic plateau north of Enterprise, from which it is separated by a northwest fault scarp.[1]

The Wallowa Range might therefore be considered as an island group surrounded by an uneven basaltic plateau, which in turn is

[1] Warren D. Smith, personal communication.

almost completely encircled by mountains except to the north, where the uplift is lower.

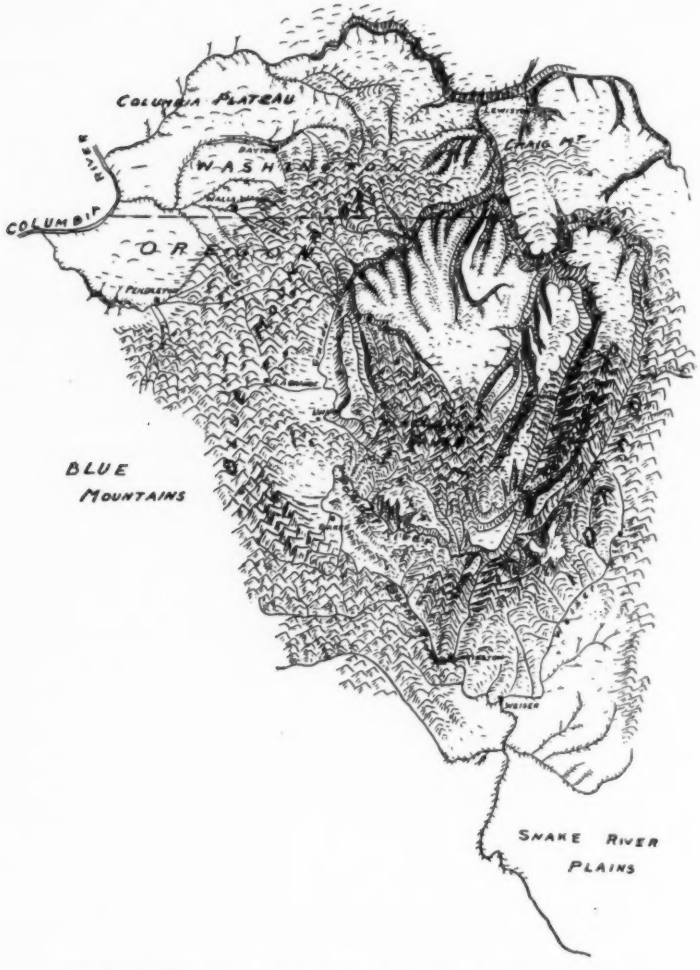

FIG. 1.—Sketch map of Snake River Canyon and adjacent territory

GENERAL GEOLOGY

The oldest rocks of the region, so far as the writer is aware, consist of a series of stratified beds which range in age from Carboniferous to possibly Cretaceous.[1] Except in a few small areas they have never been studied in detail. They are exceedingly complicated in their relation to one another because of faulting, which is both pre-Miocene and post-Miocene in age. In fact, the country which lies within the encircling rim of the Blue Mountains and along the borders and within the mountain uplifts is a mosaic of fault blocks, often obscured by basalt flows, and it will need years of patient work to fill in the details of this complex terrane.

Carboniferous, Permian, Triassic, and Jurassic fossils have been reported, and in some cases identified, from scattered localities in this region. No attempt will be made to describe these rocks as they have little bearing on the present topography. It will suffice to say that they consist of argillites of possibly more than one age, of volcanic tuffs, agglomerates, and lava flows ranging in age from the Permian to the Jurassic, of limestones and of shales. The whole series has been intruded by dikes of varying composition and of ages ranging from the Mesozoic to the basalt-filled fissures of the Miocene, which represent some of the conduits by which the vast lava floods of the Columbia basin reached the surface.

This stratified and much-faulted series of older rocks has also been intruded by granodiorite, which is well exposed in the mountain uplifts, and covered by flow after flow of basalt, which is believed to be of Miocene age.[2] Many of the streams have cut below this basaltic cap, and except in the mountains, which are chiefly of granodiorite, afford the only exposures of the underlying rocks. The presence of large areas of basaltic cover makes it extremely difficult if not impossible in some places to work out the full sequence of events.

AGE OF THE MOUNTAIN UPLIFTS

An interesting feature disclosed in this region is the age of the mountain uplifts as compared with the age of the basalt flows. In

[1] Waldemar Lindgren, *22nd Annual Report, U.S. Geol. Survey*, Part II, p. 577.

[2] I. C. Russel, *20th Annual Report, U.S. Geol. Survey*, Part II, p. 83; George Otis Smith, *U.S. Geol. Survey Prof. Paper 19*, p. 16; Waldemar Lindgren, *22nd Annual Report, U.S. Geol. Survey*, Part II, p. 592.

northern Idaho the Miocene basalt of the Columbia plains flowed up to the edge of the granitic mountains which form a part of the Idaho batholith and covered their lower slopes. The basalt flowed up many of the valleys, impounding the waters and in some cases forming lakes which are now flats or meadows. High portions of the old mountain system, such as Kamiak and Steptoe buttes in eastern Washington, rise like islands above the basaltic flood, which is remarkably level for long distances.

But in the region under discussion the mountain uplifts are later in age than the basalt flows. The Blue Mountains east of Pendleton and Walla Walla are elevated blocks of basalt rising in a series of steps, through which the granite core protrudes in the Elkhorn ridge west of Baker, the highest part of the range. The Wallowa Mountains are covered with basalt on both their eastern and western borders. In fact this condition is common in the Wallowas up to elevations of 7,000 feet and higher. Remnants of basalt are found in the more deeply eroded Seven Devils of Idaho up to elevations of 7,500 feet. Cuddy Mountain, to the south of the Seven Devils, is an elevated block of basalt, surrounded by fault scarps, which reaches an elevation of nearly 8,000 feet. It is so flat in places that an aeroplane could easily alight upon its plateau-like surface (see Fig. 2). Hitt Mountain, to the south, is rougher than Cuddy Mountain, but is also covered almost entirely with basalt. Its elevation is not known, but it exceeds 7,000 feet. On the other hand, Iron Mountain, Idaho, and Lookout Mountain, Oregon, are practically free from basalt.

If the basalt which lies on the summits of these mountains is of the same age as the flows of the Columbia basin to the north and west—and as it is continuous in that direction there is no reason to doubt this assumption—it means that the mountain system of northern Idaho, which extends southward into the central part of the state, is older than the mountains under discussion. The mountains of northern Idaho were flooded with basalt up to certain levels and formed a barrier to the flows in that direction. On the other hand the region of the Wallowas, Blue Mountains, Seven Devils, etc., was covered with basalt, and these mountains have carried the basalt to higher elevations as they rose. In other words, the

mountains of north Idaho, and probably those of most of central Idaho, are pre-Miocene in age, whereas the Wallowas, etc., are of post-Miocene age.

There is, of course, the alternative explanation that the basalt was poured out on the summits of these mountains after they were uplifted. The presence of extensive post-Miocene faulting, together

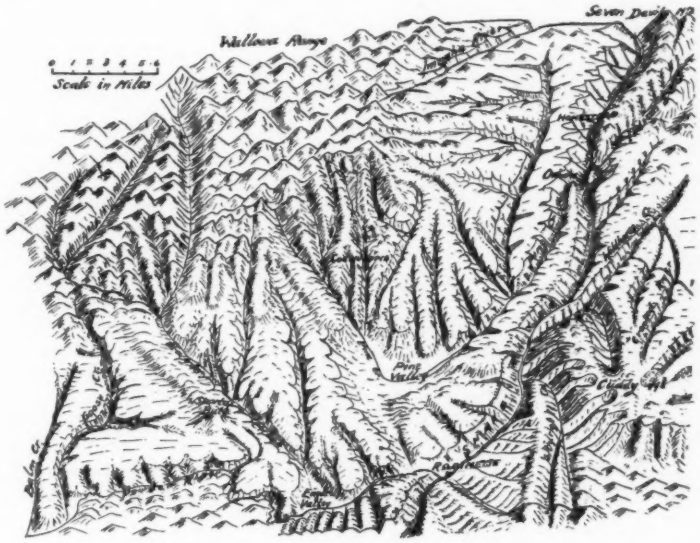

FIG. 2.—East half of the plateau region south of the Wallowa Range, part of the Wallowa Range and the Snake River Canyon.

with the evidence derived from the drainage history due to this faulting, invalidates this explanation. This evidence, which follows, shows that the Wallowas and neighboring ranges have risen along post-Miocene faults which have displaced the basaltic flows, and are younger than the basalt which rests upon their summits in many places.

Just where the border-line lies between these two generations of mountains is not clear. It may not even exist. The facts might be harmonized by allowing for a slow continuous uplift of the cen-

tral Idaho batholith, which was initiated before the Miocene and is not yet completed. This view does not conflict with Lindgren's statement,[1] that these mountains are spurs from the Idaho batholith, or mountain system. It implies, however, a vast time involved in the uplift, in which the basalt flows were incidental. If this uplift was an isostatic adjustment, the basalt flows apparently affected it very little. The lighter areas of rocks have continued to rise since the Miocene, carrying portions of the plateau to greater heights than the surrounding plateau as they did so.

POST-MIOCENE FAULTING AND THE DRAINAGE

The mountain uplifts, in many instances, are bordered by fault scarps which are in some cases traceable for miles. The Grande Ronde and Powder River valleys, in the vicinity of La Grande and Baker, respectively, are separated from the adjoining mountains by scarps (see Fig. 3). The southern border of the Wallowa Range is separated from the broken plateau region by a series of parallel and branching faults which are often expressed by scarps where they intersect the valleys. These fracture lines and scarps are of recent origin, and it is possible that some of them may be to a slight extent planes of movement today. Extensive slide rock, caused possibly by recent slipping along faults, as well as hot springs, occur along the line of some of these faults. These faults, which are post-Miocene in age, as they have displaced the basalt, are so interwoven with the development of the drainage that a discussion of the faults necessarily involves a discussion of the streams. Many of the streams show recent displacement from former channels in which movement of fault blocks has been the controlling factor.

A study of the drainage pattern shows that the streams can be classed into three main divisions:

1. A northeast system, which includes Snake River from the mouth of Burnt River, Oregon, to a point in about the latitude of Whitebird, Idaho, where its course changes; the Imnaha River; the lower part of Pine Creek and possibly the east fork of Pine Creek. All of the preceding creeks are on the Oregon side of the river. On the Idaho side are Indian Creek, Salt Creek, Wildhorse Creek, and

[1] Waldemar Lindgren, *22nd Annual Report, U.S. Geol. Survey*, Part II, p. 574.

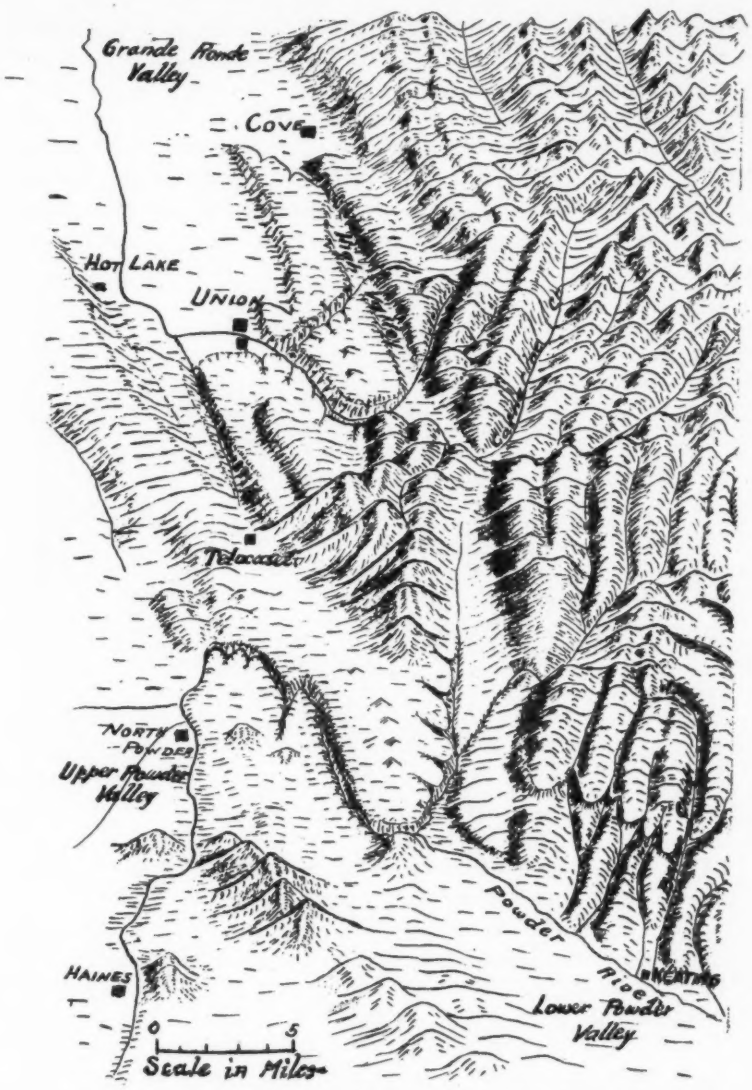

FIG. 3.—West half of the plateau region south of the Wallowa Range and a portion of the Wallowa Range.

Crooked River. The first three flow into Snake River at an abnormal angle, being nearly parallel with the Snake, but flowing in the opposite direction (see Fig. 3).

2. A northwest system, almost at right angles to the first, which includes Burnt River, lower Powder River, parts of Eagle Creek, the upper part of Pine Creek, and the lower part of Catherine Creek. The last three flow from the Wallowa Range, and their headwaters represent the third type (see Fig. 2).

FIG. 4.—Post-Miocene, northwest fault cutting an ore body at the Mother Lode Mine northeast of Baker, Oregon.

3. Radiating streams from the granitic uplifts which represent normal development on slowly rising areas.

Where these radiating streams leave the mountains, and in some cases within the mountain uplifts, they follow either one or other of the two first systems, which have been caused by recent faulting of the plateau into two principal directions. The northeast system occurs in the vicinity of Snake River, while the northwest system lies somewhat farther to the west. The northeast system is roughly parallel to the general course of Snake River, to the Seven Devils—

Cuddy Mountain uplift, and the abnormal streams, such as Indian Creek.

The northwest system is parallel to both the northern and southern boundary of the Wallowa Range and the eastern side of the Blue Mountains west of Baker. Some of these fracture lines intersect in the vicinity of Pine and Eagle valleys, Oregon (see Fig. 3), and have undoubtedly been the prime factor in the formation of these valleys, which are garden spots in an otherwise dry, inhospitable region.

RECENT CHANGES IN SOME OF THE TRIBUTARIES OF SNAKE RIVER IN OREGON

Powder River, which flows through the town of Baker, shows evidence of a comparatively recent change in its course. It heads in the Elkhorn ridge of the Blue Mountains west of Baker and meanders through the broad alluvial valley of the Upper Powder, as it is called. It continues its meandering course northward to a point a little south of Telocaset (see Fig. 2), where it makes an abrupt bend to the southeast and continues in this course to Snake River. It formerly continued northward, and the change in its course at the abrupt bend is due to a fault block of the northwest system that was tilted up across the path of the stream more rapidly than the stream was able to cut through it. This particular fault block is due to a series of parallel and branching faults that extend along the foot of the Wallowa Range from the Grande Ronde Valley at Union to Snake River, a distance of over 60 miles. The northerly face of this fault block extends northwest as a scarp that forms the southwest border of the Grande Ronde Valley. The O.W.R. & N. Railroad has to climb the face of this scarp, in going east from Union to Telocaset, by means of a fairly steep grade. Along this fault scarp are at least two hot springs; one at Union station and one at Hot Lake, which is the site of a sanitarium. This evidence is fairly conclusive that the upper part of Powder River was at one time a part of the Grande Ronde drainage system, and its present course to Snake River below Telocaset is comparatively new.

Catherine Creek (see Fig. 2), one of the main sources of the Grande Ronde River, drains the southwest corner of the Wallowa Range

and flows into the Grande Ronde Valley at Union and thence into the Grande Ronde River. This stream has apparently flowed through two other distinct channels in the lower part of its course before it occupied its present one. Its original course, after leaving the main Wallowa Range, was almost due south into what is now Powder River. It established itself here in a broad flat valley known as the Park, which is now occupied by an insignificant stream known as Beagle Creek. Its alluvial fan was no doubt an important contributing factor in the formation of the broad fertile flat of the lower Powder valley. The rising of a block along northwest fractures either cut off the original Catherine Creek in this direction or, what is more likely, caused the rapid development of a northwest-flowing stream along the line of one of the faults. This eventually beheaded the original Catherine Creek and diverted its waters in a northwesterly direction into the Grande Ronde Valley past the site of the small town of Cove, which is situated on the alluvial fan of this second Catherine Creek. It flowed in this channel long enough to develop a wide valley, the lower part of which is now dry and is known as High Valley, and the upper part of which is still occupied by Catherine Creek. Following this, a small stream working along another branch fault beheaded this second Catherine Creek and diverted its waters into the Grande Ronde Valley at the point where the town of Union now stands. The point of capture is about 8 miles above the town of Union. At this point the valley of Catherine Creek changes abruptly from a narrow, newly cut gorge to a broad and much older valley, which at one time was continuous with High Valley (see Fig. 2). The first course of Catherine Creek was due to normal development on the Wallowa uplift. The present course, as well as the second course through High Valley and Cove, was determined by post-Miocene faulting.

Pine Creek, a tributary of Snake River, shows a somewhat similar history (see Fig. 3). The course of this creek has been controlled by both systems of faulting. The west fork of Pine Creek, in the Wallowa Mountains, above the old mining town of Cornucopia, is determined by a northwest fault. This fault has brought the granite and argillites of the Wallowa uplift in contact with a complex series of tuffs and volcanic agglomerates similar to those at Homestead.

Pine Creek cuts across this fault below Cornucopia and encounters another parallel northwest fault near the head of Pine Valley, which forms the western scarp boundary of this valley. At one time Pine Creek followed this fault and drained into Powder River a short distance above its junction with the Snake. An uplift along this fault, accompanied by an uplift along an intersecting northeast fault, blocked the course of this stream in this direction and probably formed a shallow lake where Pine Valley is today. This lake probably had an outlet directly to Snake River in a southeasterly direction at one time. The lower part of Pine Creek flows along the general direction of a northeast fracture that extends from the Seven Devils Mountains in Idaho and crosses the Snake River in the vicinity of the Oxbow. A small stream by headward erosion along this fracture line from Snake River diverted the waters of Pine Creek into this channel where the creek flows today.

Some portions of Eagle Creek (see Fig. 3) have been determined by the northwest fault system, and the present form of Eagle Valley has been influenced to some extent by the same system of faulting. This valley, which is more than a thousand feet lower than Pine Valley, is a rich alluvial fan abundantly watered by Eagle Creek. Its northern wall is undoubtedly a fault scarp, evidently a part of the same system of fracturing that extends along the southern border of the Wallowa Range from the Grande Ronde Valley and caused the diversions of Catherine Creek. Eagle Valley is underlain by a great thickness of gravel which must have been brought down and deposited by Eagle Creek when the glaciers were melting in the Wallowas at the close of the Pleistocene. This alluvial fan must have completely blocked Powder River at one time. This blocking of Powder River by the Eagle Creek alluvial fan may have been a contributory cause in the formation of the broad flats of the lower Powder valley in the vicinity of Keating, due to the formation of a shallow, temporary lake at this place.

Burnt River, which lies to the south of the drainage area described before, has had its course determined by the northwest faulting system. The fault scarp which forms the boundary between the upper Powder valley and the Elkhorn ridge[1] west of Baker is

[1] Waldemar Lindgren, *22nd Annual Report, U.S. Geol. Survey*, Part II, p. 653.

along the same line as the general course of Burnt River, and both are undoubtedly due to movement along the same line of fracturing.

Indian Creek, Wildhorse Creek, and Crooked River, on the Idaho side of the Snake, have had their courses determined by northeast fracture lines. The oxbow on the Snake River (see Fig. 3), a prominent topographic feature, has been formed apparently by the intersection of the northeast and northwest fracture lines at that point. It lies on the line of Indian Creek and the lower part of Pine Creek, which are on the northeast system, and also on a line which forms the scarplike face of the north side of Cuddy Mountain, which is on the northwest system. The writer does not claim this as proved, but as the most probable explanation of this peculiar feature of Snake River.

HISTORY OF SNAKE RIVER

Snake River heads on the continental divide and flows across the plains of southern Idaho in a general westerly direction. These plains are underlain by lava flows and lake beds of late Tertiary age, and portions of these plains are covered with lava flows of more recent age. Across the plains of Idaho this stream has cut a canyon which varies in depth and has very little in common with the lower part of Snake River. At the western edge of the state of Idaho, near the mouth of Burnt River, Oregon, Snake River makes an abrupt turn to the northeast, and from this point flows through a deep and rugged canyon which is nearly 200 miles long (see Fig. 1). In so doing it has intrenched itself in this high plateau and has cut its way between two mountain ranges, the Wallowas of Oregon and the Seven Devils of Idaho. The deepest part of this canyon commences below Homestead, Oregon, and in several places exceeds the Grand Canyon of the Colorado in depth. The canyon of the Snake below Homestead, Oregon, is one of the most inaccessible gorges in the United States.

The history of this stream is not easy to decipher, but the study of the tributary streams and their relation to faulting has thrown a new light upon the history of the Snake River. The northeasterly course of Snake River, from the mouth of Burnt River almost to the mouth of the Imnaha River, is roughly parallel to the general strike of the older rocks which cross the Snake at a very low angle

and in some places are parallel to the course of the river. The general course of the stream over this distance is also roughly parallel to the northeast fault system. These two factors have largely determined the northeast course of Snake River for about 100 miles below the mouth of Burnt River.

The early history of the drainage of this region may be connected with the great Tertiary lake basin that existed in southern Idaho and extended an unknown distance into Oregon. This lake, or connected bodies of water and intermontane basins, was named Lake Payette by Lindgren.[1] According to Lindgren it existed in the Neocene, or late Tertiary, and may have been caused by the blocking of westerly drainage by the great Miocene lava flows of the Columbia basin.

There is no evidence, so far as the writer knows, that these lake basins ever had a direct westerly outlet to the Pacific across the lava fields. If there was at one time such an outlet it was soon blocked by the Blue Mountain uplift. It seems likely that, following the initiation of the Blue Mountain uplift, the excess water from these lake basins reached the Columbia by way of the Grande Ronde River. That the outlet stream was small seems probable because of the large evaporating surface which a series of connected lake basins would furnish. The supposition that the Grande Ronde was the former drainage channel of this region rather than the Snake is based on evidence at the place where it enters Snake River, and follows below.

Where the Grande Ronde River now enters Snake River it possesses a series of intrenched meanders cut in the lava flows that form the walls of its canyon. These meanders must have been formed on a flat plain or valley before the present uplift destroyed the valley. On the other hand, Snake River at this place is flowing in a comparatively straight canyon. The most probable explanation of this condition is that this canyoned part of the Snake was at one time a short tributary of the Grande Ronde, and, flowing from a higher country, had consequently a straighter course.

The supposition that the Grande Ronde once formed the main outlet of the lake country of southern Idaho and eastern Oregon is

[1] Waldemar Lindgren, *18th Annual Report, U.S. Geol. Survey*, Part III, p. 632.

based on the assumption that the Grande Ronde and Powder River valleys were once connected with the Snake River plains by way of the Burnt River and associated valleys. There is pretty good evidence of more or less continuous lake basins from Baker east to Durkee. Below Durkee, Burnt River flows through a narrow gorge cut through a recent uplift, and all evidence of the old course apparently has been destroyed by renewed erosion.

As the uplift and faulting of the basalt plateau continued, the Grande Ronde River, with its large tributary, the Snake, cut deeper and deeper into the rising plateau. This tributary stream, which is now the Snake Canyon, worked headwards to the south, receiving as it did so a greater share of the drainage from the Wallowas, the Idaho Mountains, and various scattered lake basins on the plateau and developing its course along planes of weakness. Eventually it cut into the main basin of old Lake Payette, thereby short-circuiting the drainage of the Grande Ronde. This left the Grande Ronde with about the same drainage area as it possesses today. Assuming that large evaporation from the late Tertiary lakes south of the Blue Mountains was an important factor, the amount of water carried by the Snake may be greatly in excess of that carried by the Grande Ronde before the piracy. The latter drained a flatter country with a number of scattered lake basins and a consequently large evaporation surface, while the Snake River must have drained most of these lake basins completely, thereby increasing its water supply.

This theory of the development of Snake River, beginning its career as a tributary stream of Grande Ronde River and following the lines of weakness as it eroded headward into the rising plateau, seems to fit best with the facts as disclosed by a study of the faulting and its effect upon the streams of the region.

The whole topographic development of the region, including the mountain uplifts, the structural valleys, the course of Snake River, and the drainage pattern of the tributaries of Snake River, is associated with the two series of faults that trend northeast and northwest, and can be explained on a basis of differential uplift and depression along these fault lines.

THE FRACTURING OF INCOMPETENT BEDS

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ABSTRACT

The relation of several theories of fracture is pointed out, and the important determinants of the angle of rupture are considered. The most important factor is thought to be friction which tends to localize fracturing on planes less than 45° to the axis of compression. The general assumption that fracture cleavage can best be explained by the strain ellipsoid is questioned. It is pointed out that since fracturing increases bulk, relief from compression necessitates rotation of fragments in the special case of fracture cleavage where conjugate fractures are absent. Rotation of fragments changes the inclination of the initial rupture planes, and the final result depends on the amount of readjustment as well as on the initial angle of fracturing. Thus typical fracture cleavage may be readily explained without assuming a strain ellipsoid and an obtuse fracture angle facing compression.

Swanson[2] has recently summarized some of the leading theories relating stress and strain to fracturing. He concludes that incompetent beds fracture with obtuse angles facing the direction of compression, and suggests that the strain ellipsoid may be readily used in deciphering structure in such formations but that it be used with caution in more competent beds. The present writer's studies, however, lead to the conviction that both of these conclusions are inadequately supported by theory and observation.

Competent (strong) and incompetent (weak) are relative terms, for a limestone may be less competent than a quartzite and more competent than a shale. Swanson's discussion indicates that he is primarily considering slates and shales as typical incompetent beds, and it is safe to infer that his conclusions are not meant to include rocks as strong as limestones. Compression tests, however, show that many shales break with acute angles facing the direction of compression.[3]

[1] Published by permission of the director of the U.S. Geological Survey.

[2] C. O. Swanson, "Notes on Stress, Strain, and Joints," *Jour. of Geol.*, Vol. XXXV (1927), pp. 193–224.

[3] G. F. Becker, "Experiments on Schistosity and Slaty Cleavage," *U.S. Geol. Survey Bull. 241* (1904); see Fig. 8, p. 16.

The relation between the fracture cleavage and the compression joints in Van Hise Rock[1] is not easily explained by the strain theory and led to Swanson's study. In common with most geologists, Swanson assumes that fracture cleavage represents one set of compression joints while the other set, which is not generally developed, is supposed to lie parallel to the bedding. If this relationship is demonstrable, his explanation is convincing; otherwise the explanation must depend entirely upon theory, and the theoretical basis for his conclusion is given scant attention. His fundamental assumption is questioned in the present paper, and another possibility is suggested.

Swanson has summarized many of the theories of fracturing; but the relation of one theory to another is not clearly brought out and, as a result, the causes of the observed variation in the angle of fracture are left in doubt. Since a satisfactory decision depends chiefly on a clear understanding of the determinants of rupture, the theory of fracturing will be briefly considered.

On December 29, 1926, I presented a short paper on the relations between stress, strain, and rupture before the Geological Society of America, in Madison, Wisconsin.[2] Although much of Swanson's paper is in essential agreement with mine, we differ in our evaluation of the determinants of fracture;[3] it seems worth while, therefore, to summarize the paper presented at Madison and supplement it with a discussion of fracture cleavage.

GENERAL RELATIONS BETWEEN STRESS, STRAIN, AND RUPTURE

A study of several important theories of rupture shows that there are two widely differing schools of thought. Starting with different assumptions as to the cause of fracturing, they arrive at diametrically opposite conclusions.

Becker[4] assumed that fracturing occurs where the strain is greatest, i.e., that the plane of maximum strain will be the plane of frac-

[1] C. O. Swanson, *op. cit.*, p. 211; also figures in *Leith's Structural Geology*, p. 156.

[2] T. S. Lovering, "The Relations between Stress, Strain, and Rupture in Structural Geology," *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), pp. 151–52.

[3] C. O. Swanson, *op. cit.*, pp. 207–9.

[4] G. F. Becker, "Finite Homogeneous Strain, Flow, and Rupture of Rocks," *Bull. Geol. Soc. Amer.*, Vol. IV (1892), pp. 17–90.

ture. To deal with the case mathematically, he assumes that the substance is isotropic and perfectly elastic up to the point of failure. In addition he assumes that no increase in volume occurs during compression.

If these assumptions are true, the angle between a plane of fracture and the direction of compression must always be 45° *or more;* in other words, the obtuse angle between intersecting fracture planes faces the direction of compression.

A very different theory of fracturing was originated by Coulomb and developed and modified by Navier, Rankine, Johnson, Merriman, Mohr, and others. These investigators completely disregard strain, or deformation, and consider primarily the effect of stress, or the internal resistance to an external force. A special case will illustrate the reasoning employed.

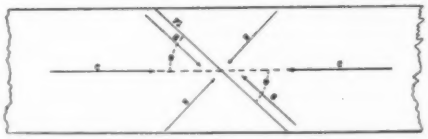

FIG. 1.—The relation of the shearing components *S* and the perpendicular or normal components *N* of a compressive stress *C*, to any plane *Pl* making an angle θ with the direction of compression which is of course parallel to *C*.

Let us consider the variation of those two components of compressive stress which are parallel and perpendicular, respectively, to any given plane which makes an angle θ with the line of compression. (See Fig. 1.) These components will vary in different ways, as indicated in Table I. Since the components parallel to a plane are the shearing components of stress and reach a maximum at 45°, Coulomb[1] thought that all fracturing should occur at this angle; the lack of agreement between theory and observation soon caused this theory to be discarded.

Movement can occur only when friction is overcome; and since friction increases as the perpendicular or normal component of stress increases, Navier[2] suggested that rupture would occur where an optimum ratio existed between the shearing components, the poten-

[1] M. O. Withy and James Aston, *Johnson's Materials of Construction* (John Wiley and Sons, 1925), p. 15. Note.—The original papers of Coulomb and Navier were not accessible to the present writer.

[2] M. O. Withey and James Aston, *op. cit.*, p. 15.

TABLE I

VARIATION OF THE EFFECTIVE STRESS COMPONENTS OF A COMPRESSIVE LOAD

Angle (θ) between Plane and the Direction of Compression	Component of Stress (N) Normal or Perpendicular to the Plane ($N = C \sin^2 \theta$)	Component of Stress (S) Parallel to the Plane (Shearing Components) ($S = C \sin \theta \cos \theta$)
0°	0.0000	0.0000
10°	0.0300	0.1710
20°	0.1165	0.3214
30°	0.2500	0.4330
40°	0.4130	0.4925
45°	0.5000	0.5000
50°	0.5870	0.4925
60°	0.7500	0.4330
70°	0.8832	0.3214
80°	0.9700	0.1710
90°	1.0000	0.0000

EXPLANATION OF TABLE I

If a given force acts along the axis of a bar of unit cross-section and infinite length, the major stress has the same value and direction as this force. Let us consider the case where there are no other forces and therefore no intermediate and minor stresses perpendicular to the bar. In any plane oblique to the axis of the bar, a measure of the normal or perpendicular, and the shearing or parallel components of stress, will depend upon (a) the area of the plane and (b) the angle which the plane makes with the direction of force. It is evident that a given force is far more effective if it is concentrated against a small area approximating the cross-section of the bar than it would be if distributed over a large surface approximating the length of the bar. The normal component (N) across any plane is numerically equal to the principal stress (C) multiplied by the sine of the angle (θ) between the plane and the stress axis, or $N = C \sin \theta$. The parallel component (S) is equal to the product of the stress and the cosine of the angle, or $S = C \cos \theta$. Since the measure of a stress depends upon the area over which the force is distributed, this factor must also be considered. In the bar specified (unit cross-section and infinite length), the area (A) of any plane will be equal to the quotient of the area of the cross-section of the bar (a) divided by the sine of the angle between the plane and the axis of the bar, or $A = \frac{a}{\sin \theta} = \frac{1}{\sin \theta}$. The true measure of the normal and parallel components respectively are evidently $\frac{N}{A}$ and $\frac{P}{A}$, or $\frac{C \sin \theta}{\frac{1}{\sin \theta}}$ and $\frac{C \cos \theta}{\frac{1}{\sin \theta}}$, which are equal to $C \sin^2 \theta$ and $C \sin \theta \cos \theta$, respectively. By substituting the functions of the successive values of θ in the foregoing expressions, Table I was compiled.

tial external friction which would develop on the shear plane, and the strength of the material. This theory more nearly accords with fact.

Several slight modifications of Navier's theory of failure have been proposed by various students of mechanics, but all are based on similar assumptions. Bouton and Johnson's theory of rupture is essentially the same as that of Navier but was derived without knowledge of Navier's[1] earlier work. Merriman[2] has substituted the idea of *internal* friction for that of *external* friction and uses the term "molecular binding force" for "strength of the material." Mohr[3] does not specifically mention friction in his theory but simply assumes that the variation in the normal or perpendicular component of stress is largely influential in determining the plane of rupture. There is little real difference in the theories of these men; Mohr's final equations can be derived quite simply from the final equations of either Merriman or Johnson.[4]

In general, these "stress" theories lead us to expect an angle of fracture of less than 45° to the direction of compression; and the formulas derived indicate that, as the coefficient of friction becomes larger, the angle of fracture becomes smaller. Johnson limited the application of his theory to brittle bodies, and here theory and observation are in fair accord. Similarly the relation between the angle of fracture and the ratio of compressive to tensile strength worked out by Mohr is qualitatively correct.

CORRELATION OF THEORIES

Three things are brought out by the foregoing discussion of theories: (1) the "stress" theories are developed from similar fundamental assumptions and arrive at conclusions in essential agree-

[1] *Ibid.*

[2] Mansfield Merriman, *The Mechanics of Material* (John Wiley & Sons, 1924), pp. 378–79.

[3] O. Mohr, "Welche umstände bedingen die Elastizitätsgrinze und die Bruch eines Material," *Zeitschr. d. Ver. deutsche Ingen.*, Vol. XLIV (1900), pp. 1524–70. See also W. H. Bucher, "The Mechanical Interpretation of Joints," *Jour. of Geol.*, Vol. XXIX (1921), pp. 1–28.

[4] I am indebted to Mr. A. C. Spencer, of the U.S. Geological Survey, for demonstrating this.

ment; (2) the "strain" theory of Becker starts with very different assumptions and as a consequence derives a result discordant to that achieved by the "stress" theories; (3) no single theory has yet been proposed that evaluates all the determinants of the angle of fracture. It is beyond the scope of this paper to discuss the mathematical relation of the determinants of rupture, but their qualitative relations may be briefly summarized.

A complete theory must consider the effect of both stress and strain; and in considering the failure of an ideal homogeneous isotropic body, the following variables must be taken into account; (1) friction; (2) the molecular binding force; (3) strain, or the elastic deformation suffered before rupture; (4) the shearing or parallel components of stress; and (5) the normal or perpendicular components of stress. The larger the coefficient of friction, the smaller will be the angle of fracture facing the axis of compression, since friction varies with the normal component. An examination of Merriman's formulas indicates that θ will vary from $0°$ to $45°$ as the molecular binding force varies from 0 to ∞. In other words, the larger the molecular binding force, the greater will be the tendency of the material to fracture with an angle of $45°$ to the compressive force. As Becker has shown, the greater the strain or elastic deformation preceding rupture, the larger will be the angle of fracture facing the axis of compression. The shearing components of stress actually cause the fracturing; and since they are decreasingly effective on planes of more and less than $45°$ to compression, they will tend to localize fracturing on planes whose angle to compression is about $45°$.

The normal or perpendicular component of stress increases both molecular binding force and friction, and thus the difficulty of causing movement on any plane increases as this component becomes larger. It is least along planes making very small angles with the direction of compression, and hence it tends to decrease the angle of fracture.

In nearly all substances the influence of friction is much greater than that of strain; and, as a result, most substances break with angles of less than $45°$ to the axis of compression. In other words, the angle 2θ in Figure 1 is usually less than $90°$. Even if we imagine a rock in which friction is non-existent, there are few that would un-

dergo sufficient elastic compression before failure to produce angles of fracture much greater than 45°. However, some highly elastic materials such as wood, soap, mild steels, and a few other substances fracture with obtuse angles facing compression.

FRACTURE CLEAVAGE IN INCOMPETENT BEDS

The partial résumé of the paper given at Madison is sufficient to indicate the relations thought to exist between stress, strain, and rupture. Passing to the special case of the fracture cleavage developed in incompetent beds, one must realize that incompetent beds are not necessarily elastic, nor need they have extremely low coefficients of friction. Thus, if friction and elastic deformation are the most important determinants of fracture, incompetent beds will not always break with the obtuse angle facing compression. We would expect a pure clay to break with a larger angle than a sandy clay, and a dry clay should break with a smaller angle than a wet one.

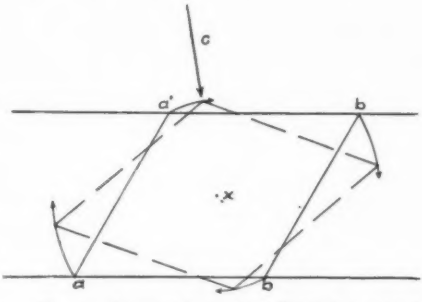

FIG. 2.—Increase in vertical dimension necessitated by too widely spaced fissures.

It is quite certain that many clays break with an acute angle facing compression. Such an occurrence is figured by Becker[1] in one of his papers on schistosity and slaty cleavage. Since Swanson reports different results in his experiments on clays, it is probable that the angle of fracture may be either less or more than 45° in argillaceous materials.

When a series of interbedded competent and incompetent strata are folded, pronounced jointing or fracture cleavage commonly develops in the weaker beds. If we assume the direction of compression to be nearly normal to the axis of the fold, we find that the angle

[1] G. F. Becker, "Experiments on Schistosity and Slaty Cleavage," *U.S. Geol. Survey Bull. 241* (1904), Fig. 8, p. 16.

between the direction of compression and fracture cleavage is commonly greater than 45°. It is this observation which Swanson offers in support of the generalization that the strain ellipsoid can be applied to the incompetent beds.

A reasonable explanation of the position of the planes of fracture cleavage is suggested by Becker's[1] partial theory of the spacing of fissures.

When a rock fractures under compression, it must crack in such a way as to relieve the pressure. Since fracturing increases the bulk of the mass, relief can only be obtained by readjustment of the fragments. If cracks were to form only at aa' and bb' in Figure 2, readjustment of this fragment would necessitate rotation about the center x. This would cause an increase in the vertical dimensions, and the pressure, far from being relieved, would be increased. In order to decrease the vertical dimensions, the fissures must be spaced at least as closely as in Figure 3, where the lower end of the crack bb' is perpendicularly below the upper end of the adjacent crack, aa'. Relief from pressure comes immediately upon readjustment of the fragment in this case, for rotation now necessitates a decrease in the vertical dimensions, as illustrated. A competent bed can withstand and transmit a compressive force that will cause fracturing in an adjacent incompetent bed. If such a condition existed when folding was taking place, there would be a strong tendency for the dimensions parallel to the compressive force to decrease and for the dimensions at right angles to it to increase. The kind of fracturing just

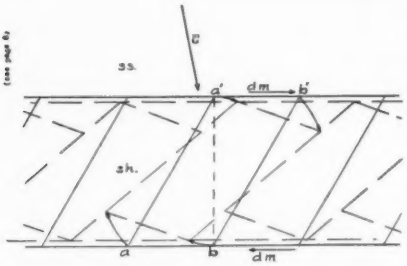

FIG. 3.—Inclination of fractures and maximum spacing of fissures that is possible in response to a compressive stress C which causes differential movement in the direction dm of the competent bed ss on the incompetent bed sh.

[1] *Ibid.*, "Finite Homogeneous Strain, Flow and Rupture of Rocks," *Bull. Geol. Soc. Amer.*, Vol. IV (1892), p. 57.

discussed would change the dimensions of the incompetent beds in this manner and is believed to account for fracture cleavage. No recourse to hidden joints (parallel to the bedding) and the strain ellipsoid is necessary in this simple explanation.

The inclination of the initial fractures to the direction of compression will depend upon the differential movement of the competent beds. If the competent bed *ss* in Figure 3 were moving from left to right, it would tend to drag the tops of the fragments in the weaker bed *sh* in the same direction, and thus aid in their rotation and the consequent relief of pressure. Thus the actual inclination will be opposite to the direction of the differential movement, as illustrated in Figure 3. On the other hand, movement of bed *ss* from right to left would work against the relief of pressure; and thus, if we apply the law of least work, we may safely conclude that this is an improbable case.

It should be understood that Figure 3 is idealized. In reality the fissures will be much more closely spaced and the ends of the fragments will be crushed into the voids indicated in the idealized illustrations. Smoothing down the shoulders of the fragments will tend to curve the upper part of the fracture planes toward the direction that the competent bed moves. It is quite possible that this minor deformation occurs largely by shear on planes essentially parallel to the bedding. To this limited extent bedding-plane joints may develop, but they will be related to a pre-existing parting plane and not to the strain ellipsoid.

From the foregoing analysis it can be seen that the final angle between the fracture cleavage and the direction of compression will depend upon the amount of readjustment that has taken place, as well as upon the initial angle of the fracture.

GEOLOGY OF SOUTHERN OAXACA, MEXICO

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ABSTRACT

Oaxaca lies at the southern end of North America proper. The surface rocks are very largely schists and granodiorite, together with some limestone. The schists and granodiorite have been reported to be pre-Cambrian. The schists are now believed to be Cenomanian, the limestone Turonian, and the granodiorite post-Turonian. There are but few extrusives. Petroleum and gas seeps occur in the general vicinity of Puerto Angel. The major structures lie in an east-west direction.

INTRODUCTION

The area under consideration lies at the extreme south end of North America proper. Beyond the Isthmus of Tehuantepec is the Yucatan Peninsula and Central America (Fig. 1).

The region is relatively accessible. Mexico City and Oaxaca City are connected by railway with an extension 60 kilometers south to Ejutla. Beyond this, trails lead south 100 kilometers to the coast. Oaxaca City is the capital of the state, and from it trails radiate in all directions to the more remote parts of the state. Towns are scattered everywhere; the Indian countryman is not inhospitable, and friendly dealings for food and lodging with him are the rule.

PHYSIOGRAPHY

At about parallel 20 the Cordilleran system swings sharply from S. 20 E. to S. 70 E. From this latitude southward to the Isthmus of Tehuantepec the major structures in the interior, however, assume an almost due east-west course. A striking illustration of this is the volcanic belt that extends across Mexico from C-Colima near the Pacific coast east through C-Toluca, Popocatepetl, Ixtaccihuatl to C-Citlaltepetl or Orizaba near the east coast. The east-west axes of the mountain ranges and the lakes are illustrations of the same phenomenon. At latitude 17°30′ in central Guerrero the axis of the

Cordillera also turns to the east and continues to the Isthmus of Tehuantepec. This east-west structure forms the southern end of the Mexican highland. The area intervening between the folded area occupied by the Cordillera and the Pacific lies in the southern part of the state of Oaxaca and is the area herein described. It is a broad monoclinal folded structure much complicated by subsidiary folds

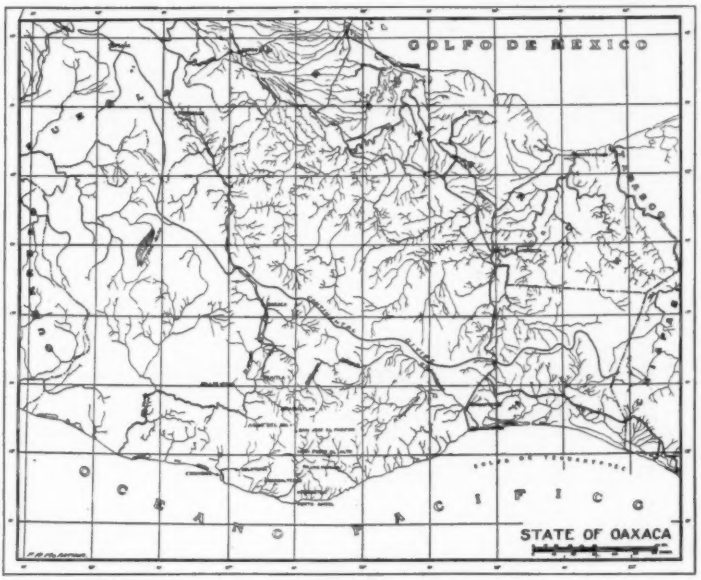

FIG. 1.—Oaxaca, Mexico

and faulting which form a series of east-west ridges paralleling the coast. The formations which occur at 6,000 and 8,000 feet on the highland reach sea-level or a few hundred feet above near the coast. The elevation of the highland varies from 5,000 to 7,000 feet with ridges and peaks rising 2,000 or more feet above this level.

Head erosion by the tributaries of the Atoyac-Verde[1] and the Mijangos-Grande systems have cut deep canyons in the highland. South of Agua del Sol the second stage of erosion has been reached;

[1] Rivers receive various names along different sections of their courses.

and the interstream areas are reduced to ridges, leaving no remnants of the comparatively level table-land. Still farther south a third stage is reached, and here the ridges have been cut by head erosion of the drainage channels, and sections are entirely isolated and left as hills.

On the east, south, and west sides the highland is bordered by a high rim. This is a noticeable feature on any traverse made from

FIG. 2.—Two views of an elevated portion of the Coastal Plain showing the mountainous country in background.

the highland to the coast. On the south side this raised border has an elevation of nearly 9,000 feet.

The coastal plain occupies the southern end of the monoclinal structure. This is a narrow belt 10–30 kilometers or more wide (Fig. 2). It apparently represents an area that was base-leveled and later elevated 100 or 200 feet. This view seems borne out by the presence of flat-topped hills having the same altitude and by the flat bed of consolidated conglomerate that forms their capping. A few well-defined benches and corresponding river terraces point to the same conclusion.

The coastal plain is a series of alternating elevated and depressed

areas. One of the latter has a lateral extent of 60 kilometers, and one of the former at least 80 kilometers. The depressed areas are characterized by high headlands and narrow drowned valleys which afford excellent though small harbors, such as those of Puerto Angel and Acapulco.

Low, monotonous flat beaches backed by an equally flat plain, often several kilometers wide, mark the elevated portion of the coast. Here ports are entirely absent and landing from boats impossible or extremely hazardous on account of the surf.

These coastal areas are apparently very unstable, and there seems to be a rhythm to their vertical movements. In one of the elevated portions there are two quite different gravel beds at different levels at some distance from the coast. These are of considerable lateral extent. The lower bed was eroded prior to receiving terrigenous deposits that lie immediately above. At the coast Upper Pleistocene with a capping of coarse beach sand has an elevation of 50 feet. These phenomena indicate at least two depressions and as many elevations. The drowned valleys and the seaward extension of the river beds for several kilometers on the ocean floor are ample evidence of the former elevation of the now depressed areas. The very great similarity along different sections of the coast between the depressed areas on one hand and the elevated ones on the other indicate that each has followed a similar history. This phenomenon of alternating depressed and elevated areas is a general one, and occurs not only along the coast of Mexico but also from San Diego to Puget Sound.

The drainage of the local area under discussion is, for the most part, accomplished by the small streams that were formed by head erosion, i.e., consequent streams, and flow directly into the ocean. Many of their tributaries, as well as sections of their courses, have east-west directions conformable to the attitude of the ridges. The streams that merit the name of rivers belong to another type. Their courses have been determined by the major structures. To this type the name "structurally adjusted" has been applied. The Atoyac-Verde, the Mijangos-Grande, and the Tequisistlan rivers are structurally adjusted streams. A still finer example is the Balsas River in the state of Guerrero.

The elevation following the growth of this part of the Cordilleran system was greater in the south than in the north. This is indicated by the fact that the continental divide is south of the middle line between the two oceans. In the Isthmus of Tehuantepec it is within 25 kilometers of the Pacific. This same condition persists south along the coast of Chiapas.

The general elevation was initiated on the western coast. This is evidenced by the lack of any Tertiary sediments on the Pacific slope. On the Atlantic side, Eocene has been found in Tabasco. Extensive Oligocene and Miocene deposits occur in Vera Cruz, and marine Upper Miocene or Pliocene has been described by Böse[1] from Tuxtepec in northern Oaxaca. This same deposit also occurs in the vicinity of Santa Lucretia at the juncture of the Tehuantepec and the Vera Cruz railroads. This general elevation is not related to the alternating depressions and elevations along the coast.

There are numerous salt and perennial fresh-water lakes contiguous to the coast. The salt lakes are confined to the borders of the elevated sections where barrier beaches have inclosed shallow coastal indentations. The saltness is largely furnished by the ocean spray that is blown over and deposited upon the land. The natives utilize this natural salt supply by washing the briny sprayed sand and evaporating the filtrates in shallow clay basins (Fig. 3). During the dry season the waves throw barriers across the mouths of the smaller streams, causing the water to accumulate in sizable lakes. With the advent of the rains, the increased volume of the rivers bursts these natural dams and the lakes are drained. The larger rivers are able to keep their channels open throughout the year.

STRATIGRAPHY

Lias or Dogger.—The oldest definitely known sediments in Oaxaca are the Jurassic at Mixteca Alta. These contain an abundant well-preserved flora that has been described in a classic work by Wieland,[2] who pronounced the beds Lias. The late Dr. Böse, in a

[1] E. Böse, "Sobre algunas faunas terciarias de Mexico," *Inst. Geol. Mex. Bull. 22* (1906).

[2] G. R. Wieland, "La flora liasica de la Mixteca Alta," *Inst. Geol. Mex. Bull. 31* (1914).

personal communication, stated his belief that these beds are Dogger. His assertion was based on the presence of marine fossils of that age in beds alternating with the land deposits carrying the flora.

Cenomanian.—The Cenomanian schists occupy by far the larger portion of the terrain from Oaxaca City to the coast. These schists are of great thickness. They are nearly everywhere badly contorted and lie at various altitudes so that accurate estimates of their thickness are impossible. Between Ejutla and the first locality to the west

FIG. 3.—Salt pans

where the overlying limestone appears, 15,000 feet of these schists are exposed. In Jalisco there are at least 30,000 feet of Cenomanian sediments, and one geologist who studied that region has given an estimate of 50,000 feet.

These schists have heretofore been ascribed to the Archean and the pre-Cambrian and were thought to be of plutonic origin, hence a word of explanation is necessary to justify the radical change now suggested. Ordoñez[1] states that the Archean rocks commence at about Zihuatanejo, Guerrero, and extend eastward, widening out and including the coastal country of Oaxaca, and that they constitute the base for the later deposits in much of Guerrero, Oaxaca, and Chiapas. In the map accompanying his report the area under dis-

[1] E. Ordoñez, "Las rocas arcaicas de Mexico," *Soc. Cient. Ant. Alzate*, Vol. XXII (1905), p. 314.

cussion is designated Archean. Felix and Link[1] refer to the schists as pre-Cambrian. Sr. José Aguilera has personally confirmed the same view.

It is believed that this interpretation is due to the lithologic character of the schists and to the failure to ascertain the relationship of the granodiorite (called granite by former writers). It has been supposed that the granodiorite was also pre-Cambrian and that the exposures were in the nature of remnants of an old land mass upon which later depositions took place. Field observation shows, however, that this granodiorite clearly intrudes the Cenomanian schists (Figs. 4 and 5) and also the Turonian limestone above. It is therefore post-Turonian. The schists are, for the most part, thinly bedded, and contain much hornblende and biotite and a large amount of quartz which weathers to rounded or subangular grains. Where fresh surfaces are exposed along the coast or by drainage channels, the schists have the hardness of granite. Graphite is widely distributed in these rocks. Locally there are beds with many nodules that suggest conglomerates that have been melted and partly absorbed by the intruding magma. Very direct evidence of their sedimentary origin is found near the town of Cozoaltepec. A small portion of the terrain escaped the molten invasion, and here the country rock is a soft shale that is unaltered except for weathering. So thorough and widespread were the effects of the invading granodiorite elsewhere that this small area is the only one thus far reported where the original state of the schists has been preserved.

These schists have the identical relationship to the overlying limestone that the Cenomanian has in many widely separated parts of Mexico. On the Atlantic side, the same stratigraphic sequence occurs in Hidalgo, Vera Cruz, and Puebla. On the Pacific slope, the same relationships are seen in Morelos, Jalisco, and Colima and are reported in Michoacan and Guerrero.[2] Near Chivela on the Tehuantepec Railway the limestone rests on a phyllite. Böse has referred

[1] Felix and Link, *Beiträge zur Geologie und Paläontologie der Republik Mexico*, Vol. II (1893–99), p. 252.

[2] For determination of the Cenomanian and Turonian, reference is made to the author's paper "Rudistids of Southern Mexico," *Calif. Acad. Sci. Occas. Paper XIV* (1928).

this phyllite to the Lower Cretaceous. In the headwaters of the Tequisistlan is a similar occurrence of the two formations. In these

FIG. 4.—Granodiorite intruding Cenomanian schists

localities there are but few or no intrusions; hence there is no metamorphism or but the little induced by shearing under pressure.

The identity of stratigraphic relationship of the schists and the limestones in this part of Oaxaca with that of the Cenomanian and the Turonian to the west, north, and east, and the great thickness of the schists, comparable to that of the Cenomanian in Jalisco, which is shown not only by its broad areal extent where steep folding is everywhere present but actually observed at Ejutla, seem to warrant the reference of these schists to the Cenomanian.

FIG. 5.—Eroded portion of granodiorite (above line), Cenomanian schists (below line).

Turonian.—The Turonian as definitely known in Mexico is exclusively a limestone. It lies unconformably on the Cenomanian and is of even broader areal distribution than that formation. It is known to occur in Tamaulipas, Nuevo Leon, Coahuilla, San Luis Potosi, Hidalgo, Vera Cruz, and Puebla on the Atlantic slope, and on the western side of the highland in the states of Morelos, Jalisco, Michoacan, Guerrero, and Oaxaca. On a traverse from the highland to either the Atlantic or the Pacific coast it is the first of the sediments to appear under the mantle of extrusives. On the western slope the thickest exposure measured is 900 feet. The persistence of the Turonian as a feature of the terrain is due not to its thickness

but rather to its hard, compact character and massive structure, which effectively resist both erosion and weathering. Here the Turonian was not deeply buried, and under the influence of orogenic forces it was broken into large blocks often several kilometers long that from a point of vantage form conspicuous features of the landscape. On the eastern coast where these sediments were deeply buried, folding as well as faulting accompanied their participation in the mountain-making movements. It weathers to steep cliffs and rugged topography that strikingly contrast with the soft outlines of the schist areas. The latter, being thinly bedded and containing an abundance of ferromagnesian minerals, readily yields to both weathering and erosion. Where the limestone is free from the effects of metamorphism, it usually has a fetid odor.

In the canyon of the Atoyac west of Ejutla the limestone carries *Apricardia* and *Radiolites* and Foraminifera. The two rudistids are clearly Turonian types. From Ejutla the formation can be traced not less than 60 kilometers north of Oaxaca City, and in the opposite direction 100 kilometers to the coast. South of Ejutla erosion has left only detached areas, while near the coast it persists only in patches.

Practically everywhere in that part of Oaxaca the Turonian carries black or gray chert nodules, which are characteristic of the same formation in Hidalgo and Vera Cruz on the Atlantic side. These are either seen in place or in the beds of streams where they have been milled and deposited.

South of San Pedro El Alto, where the granodiorite plays an all important rôle, the limestone has, for the most part, been altered to marble or, more properly, to crystalline limestone and in many places to dolomite. Near the intrusions several metamorphic minerals have been formed. Among these are muscovite, epidote, siderite, garnets, and pyrite.

Upper Pleistocene.—Upper Pleistocene beds occur in more or less connected patches from the Rio Potrero west along the coast beyond Puerto Escondido, a distance of nearly 30 miles. These carry an abundant and well-preserved marine fauna. This formation is flat lying or has locally a low dip coastward, and rests on the schists and granodiorite (Fig. 6). It has a maximum thickness of about 60 feet,

and the highest elevation recorded is 75 feet. In other places the beds are exposed only at low tide.

The movements recorded in the Pleistocene are apparently those of the coastal oscillation above mentioned and are not related to the more general folding and faulting observed along the edge of the highland.

Other sediments.—The town of Sola de Vega is located on a series of grayish-green unaltered shales that bear a close resemblance to the Papagallos shales on the east coast. As no paleontological evi-

FIG. 6.—Upper Pleistocene resting on granodiorite, Oaxaca Coast

dence is at hand, this suggested correlation is purely tentative. Their closely folded structure precludes even an estimate of thickness.

Above these shales are a few hundred feet of conglomerate. The boulder content shows a mixture of pebbles and small boulders of purple andesite, similar to a nearby andesitic flow, a fine-grained gray andesite, pink granite, decomposed purplish schist, and a few pebbles of quartz and hard gray limestone. This boulder assemblage indicates that the conglomerate is relatively recent. There is, however, no basis for even a suggested correlation of this formation.

STRUCTURE

The major structural features occurring in southern Oaxaca from the highland to the coast are the relatively flat-lying schists on the highland, the complicated anticlinal structure with an east-west axis

that forms the high rim of the highland, and the long monoclinal fold that runs from this rim south to the coast (Fig. 8). This conception is only gained by viewing the country as a whole. There are but few places where the schists are not badly contorted and fractured, thus giving to any one locality the aspect of being highly folded. However, their presence in nearly every kilometer from Ejutla to the coast—a distance of over 100 kilometers—is proof that the folds are superficial and that their magnitude is measured by but few thousands of feet and that the formation, speaking generally,

FIG. 7.—Faulted aplite dike

undulates in a relatively horizontal plane. The schistosity, however, is more steeply inclined.

The east-west structural trends are locally modified along the coast. The pressure elevating this part of the continent very evidently was from the south. The varied resistance along the front of the advancing mass resulted in differential horizontal movements and the breaking into segments a few kilometers wide separated by more or less vertical north-south shear planes. Some of these shear planes are occupied by present drainage channels.[1]

The observation relative to the horizontal attitude of the Cenomanian schists applies to Mexico as a whole. This is the case though locally the formation is highly contorted and close folding not un-

[1] For similar phenomenon on the east coast, see *Bull. Amer. Assn. Pet. Geol.*, Vol. XI (1927), p. 1204.

common. The exceedingly widespread occurrence of the Turonian on the eastern, western, and the southern coasts; its equally extended occurrence with the Cenomanian on the south and west and to a lesser degree on the eastern slope; the paucity of exposures of older rocks under the Cenomanian; and the relatively small areas occupied by younger formations, all convey the idea that the growth of this part of the continent was not accompanied by profound faulting or folding, and conveys the further idea that the terrain of Mexico is, for the most part, Upper Cretaceous.

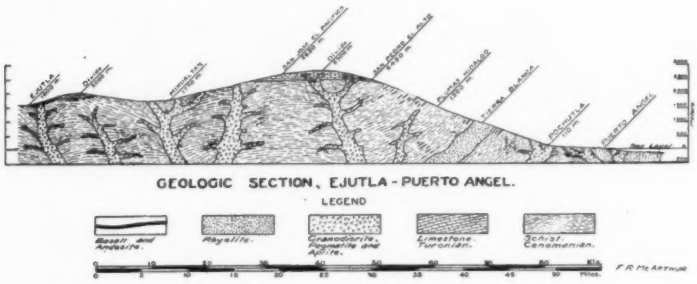

FIG. 8

INTRUSIONS

Intrusions play an important part in the geology of southern Oaxaca. Locally along the coast are a few intrusions of black diorite. These were the earliest intrusions in this part of the state. These dikes cut the Cenomanian schists and in turn are cut by the granodiorite. Their relation to the Turonian has not been observed.

There were three periods of granodiorite-granite intrusions. Of these the first was the most extensive. This period produced the widespread granodiorite intrusions before mentioned. The main body of the intrusion seems to be in a long line paralleling the coast and some distance from the present shore. Offshore granodiorite islands and granodiorite-protected points of land arranged in east-west lines parallel to the coast suggest proximity to the central mass of the intrusion. Along the present shore, branches from the larger dikes are seen to intrude the schists on every hand (Figs. 4 and 5). The thinly bedded shales and sandstones were particularly suscep-

tible to the intruding magma, as the small sills between the schist lamellae bear witness. Some of these intercalated sills are measured in millimeters. The coarse crystalline structure of even the small dikes indicates that the intrusions occurred at a considerable depth where sufficient insulation provided time for crystal growth. Inclusions of the country rock in all stages of absorption occur in the larger dikes.

In many places the country rock was melted and entirely absorbed by the intrusion, and the only evidence of its bedded origin appears in the banded structure. Only within 15 or 20 kilometers of the coast is the limestone completely marmorized. Farther inland the metamorphic effects are confined to the contact zone. The massive character of the limestone did not favor the ramifications of the intruding magma, as did the thinly bedded shales.

In Oaxaca the Cenomanian was altered to schists for a distance of at least 175 kilometers from the coast, though at this distance no intrusions are known at all comparable to those on the coast. It seems that the whole area was subjected to an intrusion that was batholithic in proportions, but that it was only in the vicinity of the coast that the larger radiating dikes reached the surface.

Wherever this granodiorite has been subjected to weathering and the surface has been protected from active erosion, it is decomposed to a considerable depth. In the town of Pochutla a water well 16 meters deep encountered nothing but soft, rotten granite.

A second period of intrusive activity is of but minor importance and has been observed only near the coast. This followed the first after a long lapse of time, as is evidenced by the slight decomposition of its rocks. Some of the intruding dikes are 5 meters wide and stand out of the decomposed granites and schists as low ridges a meter or more high.

A third intrusion is marked by still fresher granite. The magnitude of these dikes scarcely merits mention, as their thickness is measured in inches.

To this may be added a fourth series of related intrusions that occur widely distributed along the coast and nearly everywhere in the schists. These are the aplite and pegmatite dikes (Fig. 7) that represent the final stages of deep-seated acid intrusions. These dikes

are seldom more than 6 inches in thickness and very often show very clear zoning. Some of these are almost pure quartz that was evidently injected in a highly liquid state. Many of the dikes show minor faults resulting from relatively late movement.

An extensive belt of intruding rhyolite parallels the coast at a distance of 15 kilometers inland. It is a thousand feet or more wide and has an east-west extent of at least 20 kilometers. It is very acid and forms such a conspicuous feature of the terrain that it is known as the "Tierra Blanca." Fresh exposures show the presence of a small amount of biotite. The mass readily decomposes, and the colored components of the biotite are carried away, leaving a soft, very pure white rock with a slightly gray cast from the presence of small grains of magnetite. Cutting this are many small stringers of quartz. The relationship between this and the granodiorite-pegmatite series is at present unknown.

The period of important intrusions was apparently accompanied and has been followed by earth movements in the form of folding and faulting. The schists and the intruding granodiorite are both badly contorted and fractured. The relatively late aplites and pegmatites are likewise somewhat faulted, though to a much less degree.

A widely observed condition accompanied the extensive intrusions throughout their history. There is no evidence of stretching of the earth's crust or of normal faulting. On the contrary, the entire dynamic history has evidently been one of compression. These same conditions accompanied the extensive granite intrusions in the Cascades in Washington, the Siskiyou Mountains in Oregon, and the Sierra Nevada in California.

EFFUSIVES

The coast of Oaxaca shows almost no evidence of recent volcanic activity. Flow-rocks are singularly absent from the boulder content of the streams. Between San Pedro El Alto and Plumas Hidalgo the hills and ridges are capped by a fine-grained ocherous material in which reds and yellows predominate. Decay, however, has reached such a stage that a suggestion of a volcanic origin is merely conjectural. That it is not a product of the decaying schists, which it somewhat resembles, is shown by its presence on the limestone as well as on the schists, and also by its flat attitude.

North of the divide between Ejutla and Mihuatlan occur a few rhyolite dikes and a thin flow of altered andesite that is several kilometers wide. Above this and laid down on an eroded surface is a small flow of fresh basalt.

There are several local flows of rhyolite, andesite, basalt, and dacite and a few tuffs and agglomerates in the basin of the Tequisistlan. These were observed only in the vicinity of the town by the same name. It is very probable that areas of local flows are widely distributed over the country inland from the coast.

In résumé, the areal petrology of southern Oaxaca is made up of schists and granodiorite and scattered patches of crystalline limestone near the coast. At about 40 kilometers northward limestone occupies much of the terrain. A few extrusive basalts and andesites occur at 80 kilometers from the coast between Ejutla and Mihuatlan. Intruding the schists and granodiorite are numerous dikes of rhyolite, aplite, and pegmatite.

WEATHERING

Exposure to the elements decomposes the schists to a red, hydrous material called "laterite." This dries to nearly rocklike hardness. Bricks made from dried laterite and used to support a steam boiler served the purpose as efficiently as kiln-dried bricks. The weathering to hydrates rather than to oxides and carbonates is very characteristic of the tropics.

Though laterization of granites is reported to be a regular phenomenon of tropical countries, yet none was observed in southern Oaxaca. The granodiorite weathers to a sticky mass that is to all appearances entirely similar to the product of residual granite weathering in temperate regions.

In the extensive limestone areas, water rising by capillary attraction after rains has precipitated deposits of *caliche* several feet thick.

PETROLEUM

A very surprising phenomenon in this country of schists and granites is the occurrence of seeps of petroleum and petroleum gas. These have been observed on the coast at points a kilometer or more east of Puerto Angel, 7 kilometers to the west, and also inland a

kilometer north of the same town; at Pochutla, along the bank of the Rio Tonameca and east of this river. Gas and oil showings have been encountered at 1,750 and 1,850 feet in a well 7 kilometers west of Puerto Angel. So productive is the seep north of Puerto Angel that it is reported that the natives used the oil prior to the advent of the refined product now on the market.

The seeps are the more common in the vicinity of the dikes, suggesting that the intrusions afford avenues of escape.

The origin of the petroleum is entirely speculative, but two suggestions are offered. The abundant dikes at the surface may unite at depths to relatively few, thus localizing the effects of metamorphism. This would favor local distillation of oil and its retention in favorable structures from which small leaks supply the present seeps. A second suggestion is that these seeps head in the Lias, where abundant plant-remains indicate potential petroleum. It is possible that if this formation is several thousand feet beneath the surface, lateral migration from areas where metamorphic effects were not great might account for the seeps.

NOTES ON THE PRECIPITATION OF CALCIUM CARBONATE

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ABSTRACT

Some experiments—the first of a proposed series—were made to study the crystallization of calcium carbonate. Attention thus far has been directed mainly to the precipitation of calcium carbonate. It has been learned that agitation and aeration are mainly important in bringing about precipitation, and it is thought that circulation is a prominent factor in crystallization.

The writer feels that calcite should, by virtue of its widespread occurrence, serve as a better indicator of environment than it now does. Calcite crystals have a wide variety of habits about which we know little, yet each probably has a significance. It is intended to discuss here some important conditions of precipitation which it was necessary to study before attempting to study crystallization itself. Experiments were conducted to this end.

The described experiments are the first of a series planned with a view to studying the precipitation and crystallization of $CaCO_3$ under conditions intended to simulate those of nature.

The experiments were carried out for the purpose of evaluating some of the factors commonly emphasized in referring to the natural precipitation of calcium carbonate. The specific factors given consideration here are the following: (1) the effect of reductions of atmospheric pressure on a solution of calcium bicarbonate (or its equivalent); (2) the effect of agitation on the precipitation of calcium bicarbonate; (3) the effect of intimate contact of air with a solution of calcium carbonate; (4) the effect of change of temperature causing supersaturation.

All the experiments here outlined extended over periods ranging from two months for one to eight months for another. But even the longest period is to be regarded as short, and for that reason the conditions have been exaggerated with the hope of bringing about results more rapidly. This was done with a full realization of the

risk that commonly attends such exaggeration. The attempt is made to give all the conditions of each experiment in order that the reader may form his own interpretation.

EXPERIMENT I (FIGURE 1)

Two flasks which are approximately nine feet apart vertically are connected by two glass tubes in such a way that contained water may flow in a return circuit from one flask to the other. The upper flask is under reduced pressure, thereby holding up its contained water so that the lower flask may be left open to the air. In order to maintain the reduced pressure at an almost constant value, a reservoir tank was placed near the upper flask. The evolution of gas in the upper flask is accommodated by the large reservoir, which needs to be filled only once in twelve hours or more. The reservoir is filled by means of an aspirator which is fitted to the water tap. When the aspirator is turned on and the pressure reduced in the reservoir, water is drawn into it from the small overflow-flask near the lower flask. A constant stream is maintained into the overflow-flask. In this way a change in the room temperature, which affects the contents of the reservoir, is taken care of. The overflow from the overflow-flask is allowed to run down the return tube to the lower flask, thereby cooling the returning water. The temperature difference in the air of the room at the lower and upper flasks varies from 2° to 5° Centigrade. Carbon dioxide is introduced below the lower flask and bubbles are allowed to rise in the tubing to the flask. This gives a very satisfactory circulation of the water from the lower to the upper flask and return. A stop-cock and dropper in the circuit give good control of the rate of flow.

Results.—The speed of flow was varied from free flow which affords a complete circuit in about three minutes to a rate of five drops a minute. A rate of about 20–30 drops a minute was adopted for the greatest period of time as this gave the best evolution of carbon dioxide. The evolution of carbon dioxide in the upper flask despite the reduced pressure was always slight. No measurable precipitation took place. A weighed calcite nucleus in the upper flask in a period of seven months broke into several fragments. The weight of the original nucleus was 0.100+ grams. The weight of the

fragments at the end of the run was 0.126+ grams. The fact that the nucleus broke prejudices the final results, yet it is, I believe, impossible that any calcite could have traveled from the lower flask to the upper. The nucleus seems actually to have gained weight. Evapo-

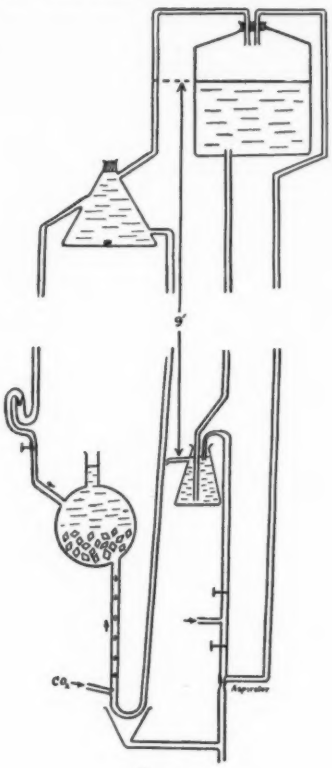

FIG. 1

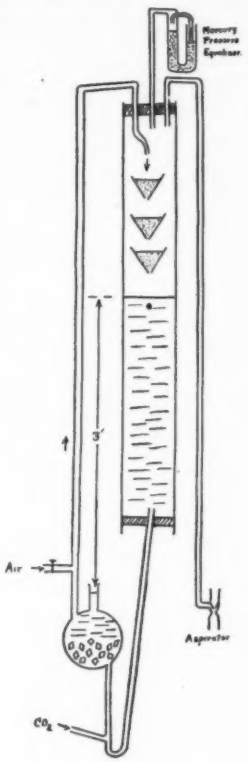

FIG. 2

ration of the distilled water placed in the system showed it to contain an appreciable amount of $CaCO_3$—the amount not being determined.

It was noticed that the small amount of agitation caused by the dropper did considerable to remove CO_2 from solution and to cause bubbles to form in the upgoing tube. This idea served as the basis for the next experiment.

EXPERIMENT 2 (FIGURE 2)

A five-foot tube, three inches in diameter, was kept half-full of distilled water by reducing the pressure above it as in Experiment 1. A tube leading from the bottom of the large tube conducts the water past a carbon dioxide intake and through a flask of calcite where the water, now saturated with CO_2, takes calcite into solution. This flask is open to air. On the outlet from this flask, at a point just above the open surface of the water, is an air intake controlled by a stop-cock. As air enters here it lifts the water over the upper bend, where it drops down through a series of funnels filled with glass beads. The purpose of the funnels is to give agitation. The reduced pressure is maintained by a simple aspirator. A pressure equalizer filled with mercury was installed at the upper end of the large tube. This prevents the pressure from being reduced too much, which would empty the calcite flask. It also assists in maintaining, in the large tube, an atmosphere low in CO_2.

Results.—This experiment was allowed to run for two months. A deposit of crystalline calcite (checked by the X-ray) was formed in all the funnels and in the up-lead tube above the air intake. The deposit was quite heavy. A nucleus placed just below the surface of the water in the large tube showed a loss in weight from 0.2617 grams to 0.2450 grams.

Two conclusions seem justified from this experiment. First, that contact with air materially assists in removing CO_2 from solution; second, that agitation is also effective as suggested by experiment 1. It seems also that the nucleus in almost still water is not in a favorable position for growth.

Lest all the $CaCO_3$ should be removed by the funnels, they were themselves removed, and the experiment run for six weeks without any growth of the nucleus.

The importance of the contact of air low in CO_2 with CO_2-saturated water suggested the next experiment.

EXPERIMENT 3 (FIGURE 3)

Three flasks, one a large water-bottle, are directly connected so that the water in each stands at the same level. In the middle one CO_2 is bubbled to saturate the water. In the next one calcite is

placed and calcium bicarbonate is formed in solution. An upright tube leads from the third flask to an aspirator at the mouth of the large flask. The aspirator, operating under fifteen pounds air-pressure, draws the water from the calcite flask and deposits it in the large flask in a very fine spray, but in so doing the water is brought into very intimate contact with air and is also vigorously and effectively agitated, which are the two conditions recognized as most important.

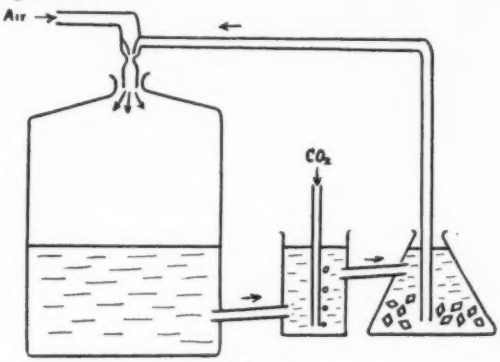

FIG. 3

Results.—A fine precipitate of calcite was deposited in the large flask and nowhere else. A nucleus in the large flask, when washed of the fine precipitate laid down on it, was found to be coated with a large number of closely-spaced calcite crystals on its upper side. These crystals were strongly fixed to the nucleus. The experiment was run for two months.

In these experiments all joints were welded glass to keep the water as free as possible from contact with other substances. Large corks, which occasionally had to be used, were covered with a heavy coat of red wax.

GENERAL CONCLUSIONS

These experiments bear out views expressed by others, and add a relative evaluation. They suggest that:

1. The contact of air with water which is saturated with calcium bicarbonate effectively precipitates calcium carbonate by removing carbon dioxide from solution.

2. Agitation of such a solution has a similar effect.

3. Reduction of gas-pressure, even much beyond any which is likely to occur in nature by changes in atmospheric conditions, has an effect, but a very small one indeed.

4. In quiet water, calcium carbonate is likely to precipitate as a fine powder. And vice versa, in circulating water it precipitates in distinctly coarse crystalline form.

It is proposed next to apply these principals to the growth of calcite crystals and of oölites of calcite.

EXPERIMENT 4 (FIGURE 4)

A flask, filled with water and containing some calcite, is connected as shown to a second flask in such a way that, on heating the

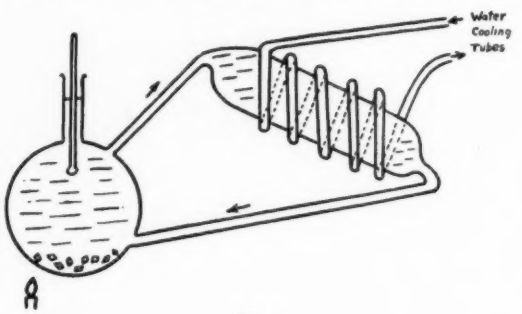

FIG. 4

first flask and cooling the second, a convection current of water is established. The temperature of the first flask was maintained at 50°–60° C. for eight months. The lower end of the second flask was kept quite cool. By simple supersaturation on cooling there was formed a host of very small crystals in the cooled flask. These crystals grew regardless of nuclei placed there. No large crystals grew.

It is proposed to repeat this experiment, making the second flask small and cooling it more effectively than by means of rubber tubing wrapped around it for circulating water. This will have a twofold purpose; first, it will better bring about supersaturation, and second, the greater speed of circulation past the growing crystal, due to the smaller size of flask, should favor the growth of one or two crystals

instead of several. It seems that movement or flow is necessary to grow large units.

EXPERIMENT 5 (FIGURE 5)

This experiment is described with considerable hesitation, partly because it shows a departure in the writer's views from the popularly accepted methods of crystal growth, but mainly because it seems unlikely to yield positive results.

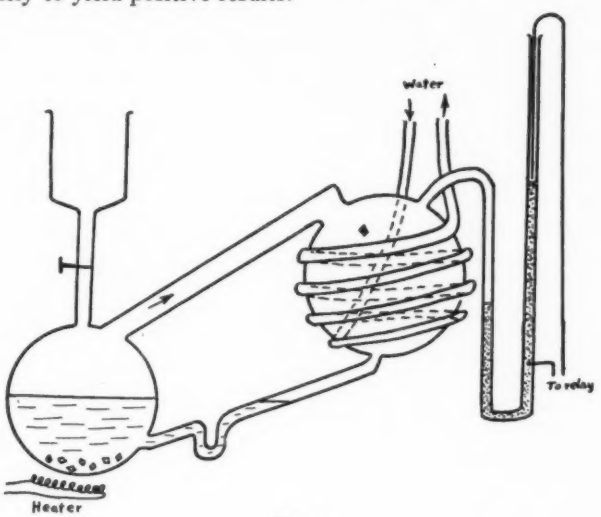

FIG. 5

There are certain chemical distillation procedures in which it is found difficult to prevent salts in solution from passing over into the distillate in small quantities. The method possibly is a mechanical transportation of solid material by moving vapor. It suggests to the writer a concrete means for the transportation and deposition of crystalline materials by heated vapors, such as those closely related to igneous activity. Some such means of transportation is needed for crystalline substances as epidote, calcite, etc., which grow in cavities in a way and under conditions that are not easily explained. On the other hand, there is reason to believe that such vapors may dissolve or etch crystals, actually rounding previously formed crystals.

A flask half-full of distilled water, in which is some calcite, is heated electrically and the vapor is condensed in another flask which is artifically cooled. A nucleus suspended in glass wool is placed in the second flask. A U-tube mercury manometer with two electric contact points leading to a relay serves to turn off the heat when the pressure (or temperature) becomes too great. The nucleus was so placed that it received the current of steam directly. The temperature was kept at approximately 100° C. for nine months.

The nucleus suffered a loss in weight from 0.280+ to 0.243+ grams. The crystal was dissolved or etched and the edges were rounded. It is hoped to try the same experiment again at a higher pressure and temperature to learn if there will be a change in the results.

The experiments are being carried out in the geological laboratories of the University of Wisconsin. The writer was materially assisted in the experiments by Mr. W. P. Rand.

ENCOURAGEMENT OF PRE-CAMBRIAN PALEONTOLOGY

DAVID WHITE
National Academy of Sciences

Under the terms of a trust recently made by Mrs. Mary Vaux Walcott, in memory of her late husband, Dr. Charles Doolittle Walcott, a fund to be known as the Charles Doolittle Walcott Fund for the promotion of knowledge of pre-Cambrian life was, in April, established under the auspices of the National Academy of Sciences. Notable features of the terms of the gift are:

The fund is to be known as the CHARLES DOOLITTLE WALCOTT FUND, and is to encourage and reward individual achievement in advancing our knowledge of pre-Cambrian life and its history in any part of the world.

The income of the fund, except the small amounts that may be allowed for administrative expenses, shall be used for the award of medals and honoraria to persons between the ages of 21 and 48 years, the results of whose published researches, explorations, and discoveries in pre-Cambrian life and history shall be judged by the Trust Fund Board to be most meritorious.

The awards shall be made without respect to nation, race, sex, or academic degree.

From the income there shall be provided a medal, to be known as the Charles Doolittle Walcott Medal "for the promotion of the knowledge of pre-Cambrian life," which medal shall be awarded every five years, beginning with 1932. Should there fail at the end of any five-year period work worthy of the award, in the judgment of the Board, the funds shall accumulate until an award is deemed justified, and a new series of 5-year periods shall commence with such delayed award.

The medal shall be cast in bronze or some other inexpensive metal, and the accrued income, after paying the expenses of coinage and minor expenses, shall, on the same occasion, be awarded, in the round sum of the highest even hundreds of dollars, as an honorarium to accompany the medal.

The award shall not be made to the same recipient on two successive periods.

The funds, amounting to $5,000, shall be held in trust by the National Academy of Sciences in the same manner as similar funds now in its keeping.

All awards of medals or honoraria from this fund shall be made on the

recommendation of a board of five members, to be known as the CHARLES DOOLITTLE WALCOTT TRUST FUND BOARD, which is to be composed as follows:

a) The Secretary of the Smithsonian Institution (*ex officio*).

b) Two members eminent in the paleontology of early Paleozoic formations, one to be appointed by the Institut de France, and one by the Royal Society of London.

c) Two members distinguished in Paleozoic paleontology, to be appointed by the President and Council of the National Academy of Sciences.

The Board shall report to the Council of the National Academy of Sciences, to which its recommendations covering the awards of medals and honoraria shall be submitted for approval, not later than February 1 of the year in which the award is to be made.

The awards shall be made under the auspices of the National Academy of Sciences and preferably at its annual meetings.

This foundation should have marked effect in the stimulation of interest on the part of paleontologists in the search for and systematic study of traces of pre-Cambrian life, a field to which Dr. Walcott contributed more than any other paleontologist. Mrs. Walcott faithfully reflects Dr. Walcott's expressed views in providing that by far the greater part of the income, which in the course of five years should exceed $1,000, shall go as an honorarium, instead of for precious metal in the medal; and, further, that the awards are to aid and encourage pre-Cambrian studies by young paleontologists.

REVIEWS

Plants of the Past. By F. H. KNOWLTON. Princeton University Press, 1927. Pp. xix+275; plates, 1; text figures, 90.

This posthumous work of F. H. Knowlton, which was fortunately completed before his death, is at present the only general paleobotanic book in the English language which might be used as a textbook in universities or as reading material for geologists and botanists who wish to inform themselves on the subject of paleobotany. Dr. Knowlton constructed his book against a very broad background, dealing with some of the elements of botany and geology, also discussing the origin of life and the pre-Devonian floras so far as they may be conjectured. When he gets to Devonian time he is on more solid ground, and the nearer he comes to the Mesozoic and Cenozoic the more he is at home. The book is fairly well illustrated, but a subject which is so unfamiliar to most of its readers could stand a great many more illustrations. If we compare Knowlton's book with the latest German publication on the same subject, Hirmer's *Handbook of Paleobotany*, which has 817 text illustrations and 708 pages, we feel that Knowlton's book should have in proportion about 300 illustrations instead of 90.

The greatest usefulness of the book would seem to be as reading material for students of paleobotany who wish to instruct themselves on the subject without being able to take a university course in it. We have tried to use the book as a textbook in classes, but it serves better for collateral reading. Knowlton has never been a teacher, and was, like most paleobotanists, an autodidakt. He knew better how to write for people who wanted to instruct themselves than for people who wanted to instruct others. Undoubtedly if the book did not pretend to be a "popular account of fossil plants," it could have been made a great deal fuller, especially with regard to the morphological side of paleobotany. As the book now stands, morphology is practically omitted, and yet the book does not give enough details about the habits of plants to make it a convenient textbook for determination of fossils, nor does the book go into the details of geologic horizons sufficiently to satisfy the needs of a stratigraphic paleobotanist.

It seems to the reviewer that there is a great need at present for more technical textbooks of paleobotany, dealing either with the biologic side, a need which is at present fairly well supplied by Hirmer's German

handbook, or with the details of stratigraphic distribution of plants, something which Sir William Dawson attempted in 1880 and which has not been repeated in the English language. The German literature has a book by Gothan on the distribution of the fossil plants in the Carboniferous and Permian; this book forms a volume of Gürich's *Leitfossilien*, a text in stratigraphic paleobotany. The English language needs another book on stratigraphic paleobotany, and Knowlton would have been eminently fitted to supply the book instead of this popular text, which is useful in its way, but the science would have been better served by a more detailed and more specialized textbook.

A. C. N.

Leitfossilien der Trias, Wirbellose Tiere und Kalkagen. By C. DIENER. Berlin: Gebrüder Bortraeger, 1926. Pp. 118; plates, 28, text figures, 27.

This book is the fourth volume of the series called *Leitfossilien* (index fossils), edited by Georg Gürich. The first volume contains the Cambrian and Silurian, by G. Gürich; the second, the Devonian, by the same author; and the third, the fossil plants of the Carboniferous and Permian, by W. Gothan.

The author describes the Triassic index fossils from various groups of invertebrates, as well as from the calcareous algae, and illustrates them on twenty-eight plates. There is also a tabulation of these fossils according to their stratigraphic distribution. The main deposits of the Triassic formation all over the globe are considered, but the German Triassic receives more space than the others.

It is to be expected that this publication will prove of great value to stratigraphic geologists and paleontologists.

A. C. N.

Minerals and Mineral Substances of New Zealand. By P. G. MORGAN. *New Zealand Geological Survey Bulletin 32.* Wellington, 1927. Pp. 110 (quarto). *5s. 6d.*

Los Minerales de Colombia. By R. L. CODAZZI. Bogota: Museo Nacional, 1927. Pp. 150.

The first of these is a typical and apparently very complete regional mineralogy, listing the minerals in alphabetical order, giving localities and references. Two folding maps are included. The second work is an educational museum handbook covering crystallography in general and the minerals of Colombia in particular.

D. J. F.

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